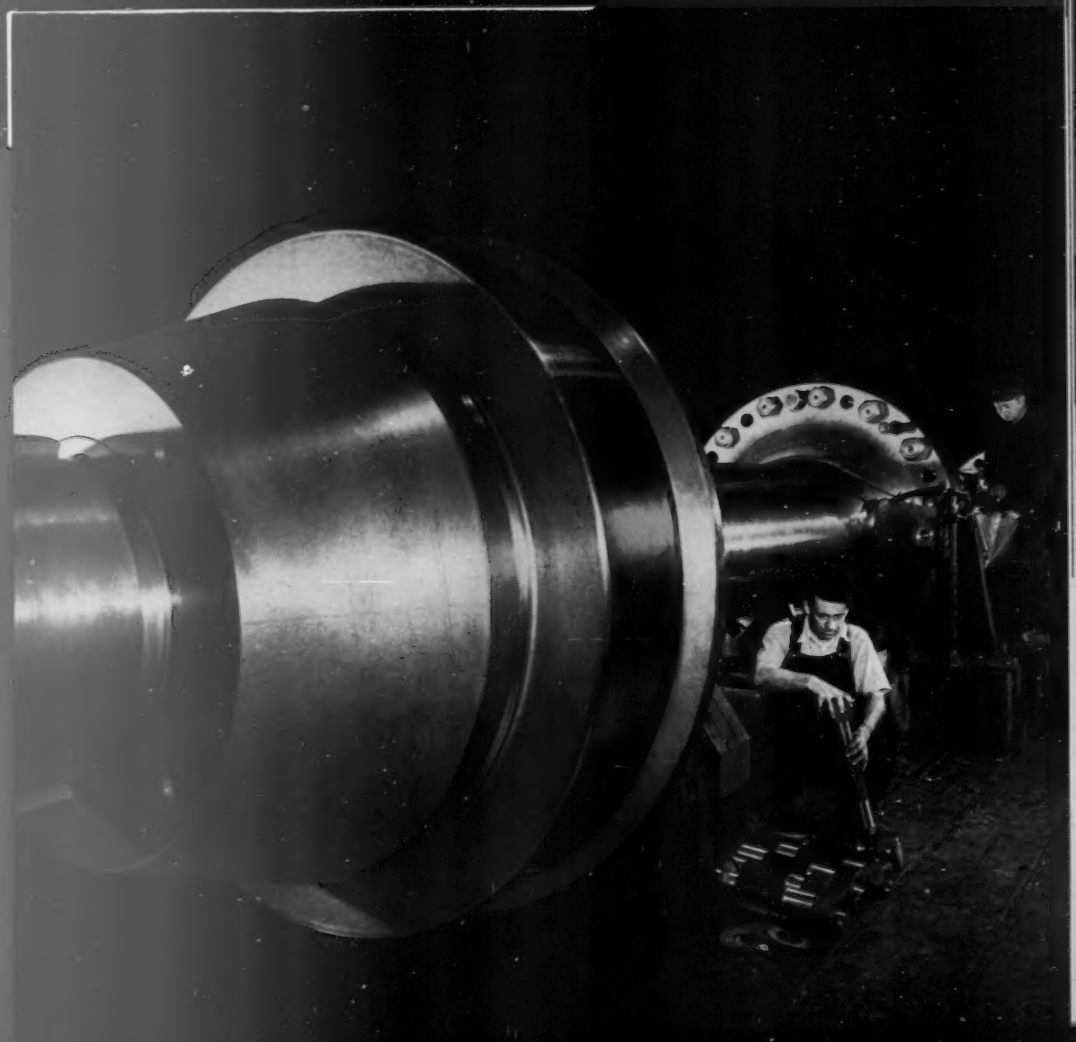
ALLIS-CHALMERS

# ELECTRICAL REVIEW

September • 1939



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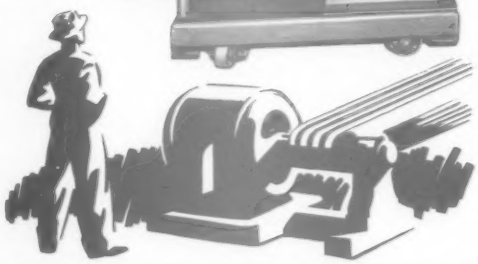

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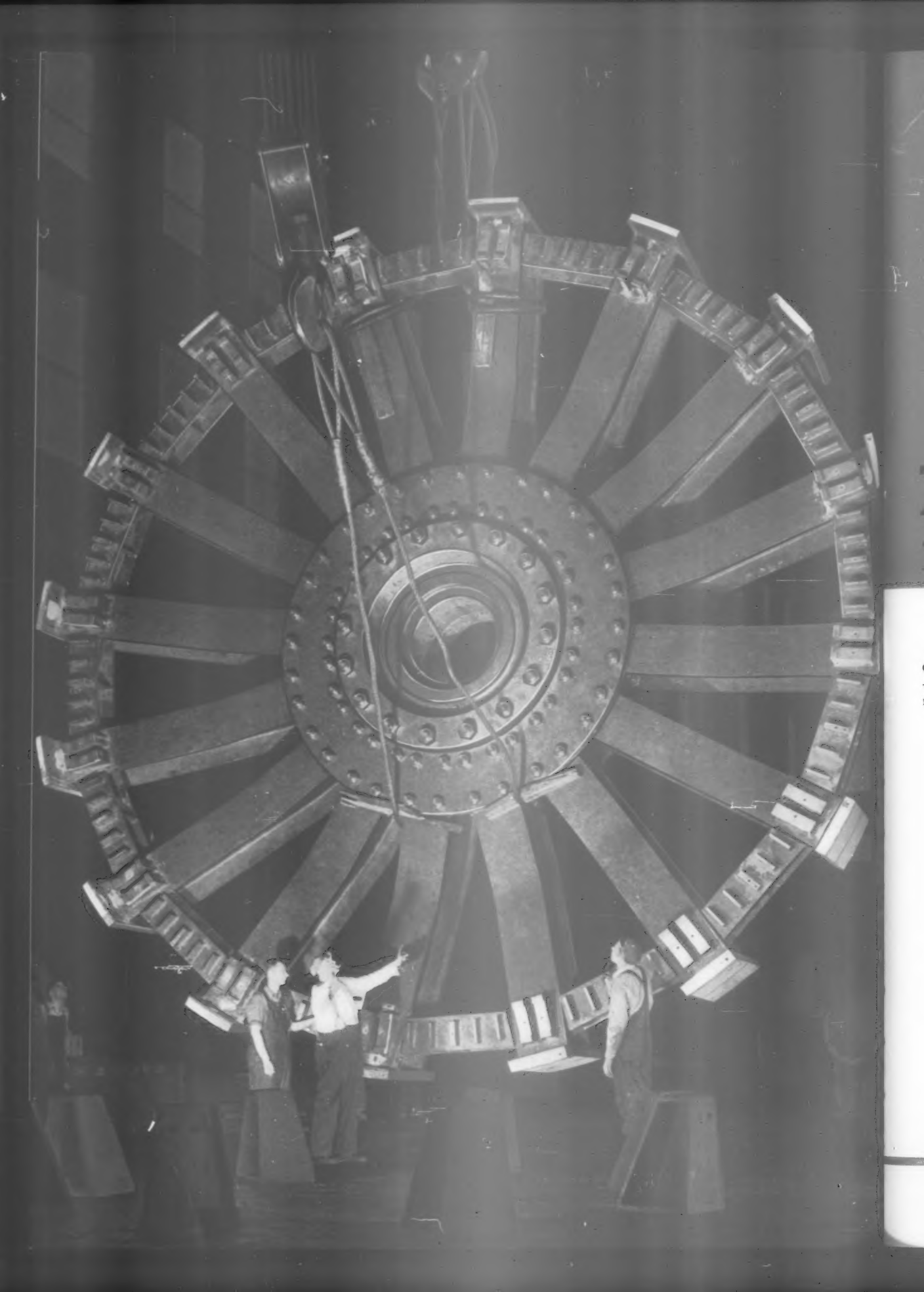

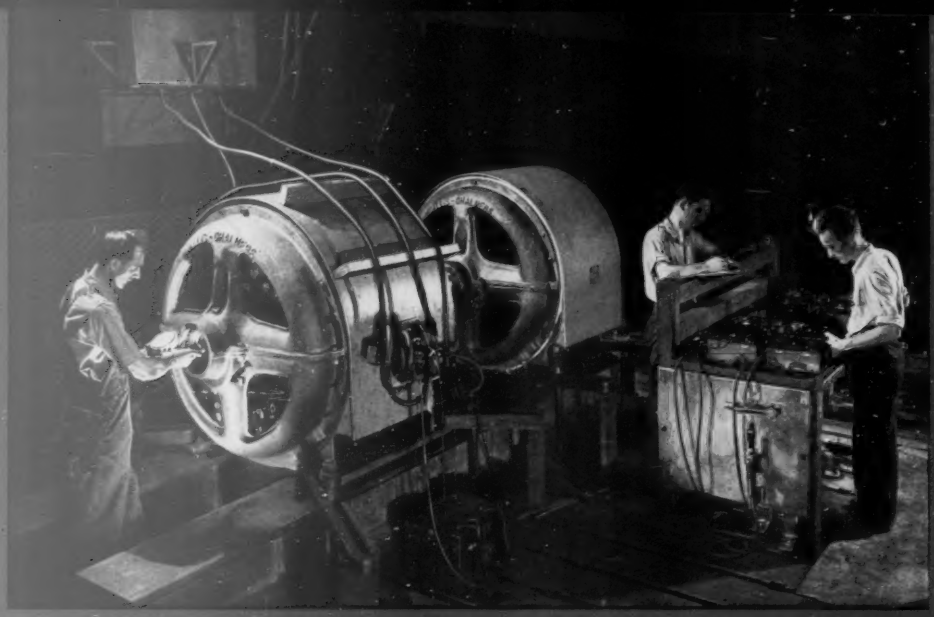

# THE CIRCLE DIAGRAM AND THE INDUCTION MOTOR

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## PART I†

● There are three generally accepted methods of determining the performance of an induction motor — the analytical method, the equivalent circuit method, and the graphical or circle diagram method.

It is not the purpose of this article to discuss the relative merits of each of these various methods but rather to present the third one in simple form so that the results obtained with its use will be in close agreement with the actual performance of any given machine.

It is advantageous to determine the performance of an induction motor from a few simple no-load tests that can readily be made, as it is not always possible, especially on a large motor, to ascertain these data by means of actual load tests.

While simplicity is desirable, there are some peculiarities in the designs of many machines that must be recognized if reasonably accurate results are to be obtained. As will be shown later on, there are some types of induction motors that require a different graphical analysis from others, and there are other types for which the usual circle diagram has to be modified, or to which it is not even applicable.

A motor with a saturated magnetic circuit requires a different analysis from one that is not saturated, and other motors which usually require special analyses are:

1. Motors having unusually large magnetizing currents.*
2. Motors (generally from fractional horsepower size up to four or five hp) which have a very high primary impedance drop.
3. Squirrel cage motors built to produce very high starting torques. These may be of the deep bar type** or of the double squirrel cage type.

If the type of motor is determined in advance, the method of precedure is quite definite. A study of the results of the no-load tests combined with a knowledge of the type or the structural features of the machine usually determines which of the graphical treatments may or may not be used.

The majority of motors are of the standard type used for ordinary industrial applications. The sizes range from five hp up to 5000 hp and larger, in both squirrel cage and slip ring types.

The equations and discussions which follow pertain to three-phase motors only.

† This article has been divided into two parts. Part II will appear in the December, 1939, issue of the Allis-Chalmers ELECTRICAL REVIEW.

ABOVE: Typical induction motor factory test set-up.

AT LEFT: Dwarfed — by the giant spider for a water wheel generator, 45 foot outside diameter.

* See Appendix I (will appear with Part II).
** See Appendix II (will appear with Part II).

## • The fundamental circle diagram

The ideal circle diagram is applicable only when steady-state conditions of the power supply exist and when there is no saturation in the magnetic circuit of the induction motor throughout its entire working range from full speed to zero speed. A simple geometric proof, neglecting the magnetizing current, is given below. Referring to Fig. 1,

If OE = impressed voltage

BE = reactance drop = $2\pi IfL$

and OB = resistance drop = IR

then, as the angle EBO will always be a right angle, the point B, for different values of current I, will always travel around the semi-circle EBO.

If OA represents the load current I for any given condition, the angle BEO = the angle BOM. Since the reactance is constant, BE is directly proportional to OA; and as triangles OAM and EBO are therefore similar, the locus of the point A is also a semicircle, which is OAM in Fig. 1.

The locus of the point A will always travel on a true circle, the semicircle of which is OAM, Fig. 1. Consequently, the word "circle," used as a prefix to the diagrammatic method of ascertaining performance, has come into general use.

## • Test data for determining the circle diagram

Because a great many induction motors, particularly those having two, four, six, and eight poles, have some degree of saturation in the magnetic circuit, great care must be exercised in preparing graphical data so that the results of the calculations will be in fair agreement with the data that would be obtained if actual performance tests were made.

If, for example, it is desired to determine the circle diagram of a squirrel cage type induction motor, the motor should be run at full speed and rated frequency without being connected to any load. A series of readings with varying voltage should be taken so that curves which are an average of all points can be drawn. If only a single point were taken, it might happen to lie off the curve. The curve of volts-amperes is shown by "A" of Fig. 2, and the curve of volts-kilowatts is shown by "B" of Fig. 2.

By extrapolating the volts-kilowatts down to the abscissa as shown by the dotted line, a value of WF is obtained, and this value represents the kw windage and friction loss of the motor at practically synchronous speed.

At the rated voltage of the motor, the kw input and the amperes magnetizing current $I_o$ can be taken directly from the curves. The kw input is made up of windage and friction loss, core loss, and the primary copper loss due to the magnetizing current. The rotor copper loss at no-load is neglected.

If it is desirable to know what these various losses are, the copper loss due to the magnetizing current, sometimes called the "idle copper loss," is obtained as follows:

(1) Idle copper loss kw = $\dfrac{1.5\ I_o^2\ R_p\ T_s}{1000}$

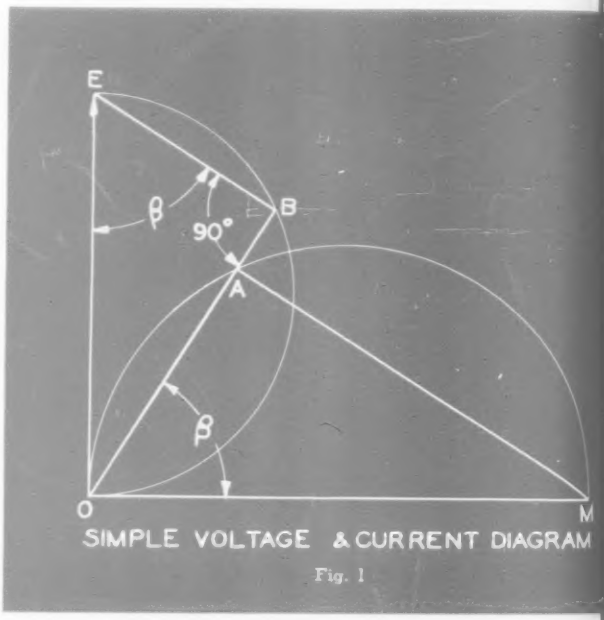
where $R_p$ = stator resistance terminal to terminal at 25°C in ohms

$T_s$ = temperature multiplier (see equations (6) and (7))

As the windage and friction loss is already known,

(2) Core loss = kw input − (windage and friction loss + idle copper loss)

In the case of an unsaturated motor, the rotor is blocked so that it cannot turn, and another series of readings should be taken with varying voltage;



SIMPLE VOLTAGE & CURRENT DIAGRAM

Fig. 1

see Fig. 3. Where slip ring type induction motors are involved, a potential that will give one and one-half to two times full load current is all that is necessary to establish the straight line curves of current and power component. Where squirrel cage type induction motors are being tested, the short-circuit curve might be taken up to two or three times full load current.

For any locked rotor test, the rotor should be so set that its position will give "average" results.

This can be done by impressing a fairly low voltage on the stator and adjusting the rotor position to that corresponding to the "average" current reading on the ammeter. This procedure is especially important on slip ring type motors.

The points on the ampere power component $I_{wsc}$ curve are obtained from the kw input on short circuit, expressed in terms of true power current as follows:

$$(3) \qquad I_{wsc}=\frac{\text{kw input}}{E\sqrt{3}}\times 1000$$

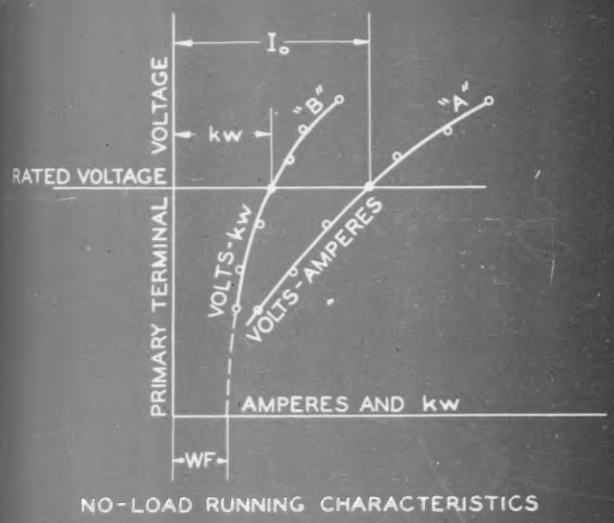
where E = the terminal voltage at any point on the short-circuit curve.

Wherever possible it is always desirable on squirrel cage motors to take the short-circuit measurements up to full voltage in order to determine whether or not there is any magnetic saturation in the machine. At the same time it is also desirable to supplement these data by a static torque curve. This curve will give a valuable check on the starting torque characteristics as determined by the kw, which are transformed into $I_{wsc}$, or amperes power component, have been taken only up to approximately two and one-half times the rated full load current of the motor. These points can be plotted to any convenient scale, and the ampere curve, starting from the origin, extrapolated in a straight line until it intersects the rated voltage line at $I_{sc}$, Fig. 3. Likewise, the power component curve $I_{wsc}$ is extrapolated to the point $W_{sc}$ corresponding to the short-circuit current point $I_{sc}$.

From the test data plotted in Figs. 2 and 3, there is enough information to construct the first simple circle diagram.

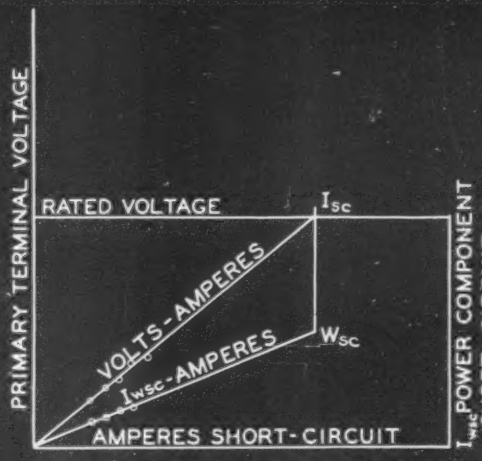
## • The circle diagram of the unsaturated motor

In order that the vectors of the circle diagram will be correct not only as to magnitude but also as to phase displacement, all vertical ordinates are plotted in "in phase" amperes determined from the kw or energy, and all horizontal abscissae are plotted in "quadrature" or "wattless" amperes. Both



NO-LOAD RUNNING CHARACTERISTICS

Fig. 2



SHORT-CIRCUIT CHARACTERISTICS
UNSATURATED CONDITION

Fig. 3

graphical method. If the points of the volt-ampere curve lie in a straight line right up to full voltage, the motor is considered an unsaturated machine. If the points of the curve begin to bend over as the voltage rises, the motor is considered a saturated machine. These differences between saturated and unsaturated machines will be explained in detail later on.

For Fig. 3 the motor is assumed to be unsaturated. The short-circuit current and short-circuit the ordinate and the abscissa should have the same scale. This may be any convenient scale. The diagram can be constructed for any given voltage, which is usually the rated voltage of the motor.

The amperes power component is calculated from the kw input of the motor running idle at the assumed voltage by the equation:

$$(4) \qquad I_w=\frac{\text{kw}}{E\sqrt{3}}\times 1000$$

To construct the circle diagram of the unsaturated motor, Fig. 4, proceed as follows:

1. *Draw parallel to OM a line $I_oP$ at a distance above OM in the vertical direction of $I_w$ from equation (4).
2. Using O as a center, scribe the magnetizing current (from Fig. 2) to intersect the line $I_oP$ at $I_o$.
3. **Using O as a center, scribe the short-circuit current $I_{sc}$, the magnitude of which is taken from Fig. 3.
4. Draw a line parallel to OM at a distance $W_{sc}$ (from Fig. 3) above OM and intersecting $I_{sc}$ at $T_{sc}$.
5. Using a compass with its center on the line $I_oP$, scribe a semicircle drawn through the two points $I_o$ and $T_{sc}$. The center of this circle is $C_{sc}$.
6. Lay off to scale above the line $I_oP$ the stator copper loss component $S_{sc}$ for the short-circuit current $I_{sc}$ (see equation (6) ).

The remaining value $R_{sc}$ measured down from the point $T_{sc}$ is the rotor copper loss component.

The division line $I_oN_{sc}$ should be drawn from $I_o$ as shown in Fig. 4. This completes the circle diagram for the unsaturated induction motor.

When it is not possible to make direct readings of slip under various load conditions, the total copper loss for both stator and rotor is represented in power component amperes by $W_{sc}-I_w$ for a short-circuit load current $I_{sc}$. The rotor copper loss in power component amperes is:

(5) $R_{sc}=W_{sc}-I_w$—stator copper loss in power component amperes

Where the stator copper loss in power component amperes is:

(6) $$S_{sc}=\frac{1.5\,I_{sc}^2\,R_p\,T_s\,k_s}{E\sqrt{3}}$$

and the stator copper loss in kw is

(7) $$S_{c1}=\frac{1.5\,I_{sc}^2\,R_p\,T_s\,k_s}{1000}$$

where $T_s$ = a factor greater than 1.0 depending on the temperature of the stator coils.

The temperature for each different loading could be taken from an assumed load-temperature curve, but for simplicity and in accordance with A. I. E. E. Standards No. 9, dated June, 1927, and A. S. A. Standards C50-1936, the temperature is taken as 75° C for all loads. On this basis $T_s=1.19$.

* See Appendix I (will appear with Part II).
** See Appendix II (will appear with Part II).

The factor $k_s$ covers stray loss. Depending on the size and type of machine, it may vary from 1 to 1.10 or more. For the determination of the "conventional efficiency" as defined in A. I. E. E. Standards No. 9, the stray loss is neglected. The A. S. A. Standards C50-1936 do not normally include stray loss. For simplicity $k_s$ will be taken as 1.00, unless it is deemed desirable and feasible to endeavor to determine these losses by one or more of the several methods described in the A. I. E. E. Test Code No. 500 of August, 1937.

## • Interpretation of the circle diagram of the unsaturated motor

From the circle diagram of the unsaturated motor, the characteristics as to power factor, efficiency, torque, etc., can be closely calculated as follows:

In Fig. 4,

(8) max. torque in synchronous hp $=\frac{mt\times E\sqrt{3}}{746}$

where E = terminal voltage.

(9) static starting torque in synchronous hp $=\frac{R_{sc}\times E\sqrt{3}}{746}$

Locked rotor stator current $=OT_{sc}$ or $I_{sc}$.

At any load point, such as "a" in Fig. 4,

Oa = primary current in amperes.

(10) hp output of motor $=\frac{ab\times E\sqrt{3}}{746}$

(11) kw rotor copper loss, $R_{c1}=\frac{bc\times E\sqrt{3}}{1000}$

(For other expressions of $R_{c1}$, see equations (12), (23), and (25).)

As bc is small, especially at light loads, and difficult to scale, more accurate results can be obtained by using the equation:

(12) kw rotor copper loss, $R_{c1}=\frac{R_{sc}\times E\sqrt{3}}{1000}\left(\frac{I_oa}{I_oT_{sc}}\right)^2$

(13) kw total input $=\frac{af\times E\sqrt{3}}{1000}$

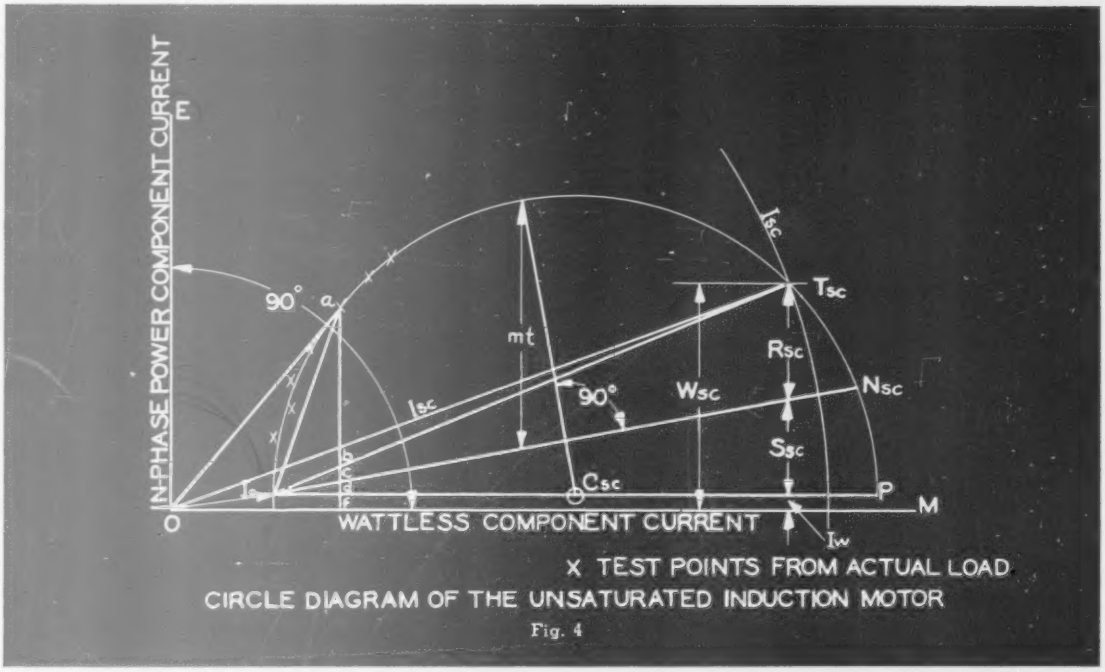
(14) % efficiency $=\frac{ab}{af}\times 100$

(15) % power factor $=\frac{af}{Oa}\times 100$

(16) % slip $=\frac{bc}{ac}\times 100$

(17) ft-lb torque $=\frac{\text{hp output}\times 33000}{2\pi\times\text{actual rpm}}$

(18) and also $=\frac{ac\times E\sqrt{3}}{746}\times\frac{33000}{2\pi\times\text{synchronous rpm}}$




CIRCLE DIAGRAM OF THE UNSATURATED INDUCTION MOTOR

Fig. 4

If it is possible to apply load to the motor, the graphical circle can be verified as follows:

For various loads with constant rated voltage and frequency, measurements are made of the current, kw input and the slip. If the graphical circle is correct, the points of current and power component should lie along the circle as shown by the crosses in Fig. 4.

The power component in amperes for any loading

$$(19) \qquad = \frac{\text{kw input*}}{E\sqrt{3}} \times 1000$$

Using O as the center, swing any given current (such as Oa in Fig. 4) to a point "a" so that the vertical distance of "a" above OM (af in Fig. 4) is equal to the power component obtained from equation (19). Point "a" should then fall on the circle.

The slip gives a direct check on the graphical method of determining the rotor copper loss bc above. Several reliable methods of determining slip are:

(1) By means of a slip meter composed of a small synchronous motor connected to the same source of power as the motor being tested. Through suitable gearing this small synchronous motor drives a pinion on one side of a differential gear cage. By means of the center hole the pinion on the other side of the differential gear is driven by the main shaft of the motor of which the slip is to be determined. If both pinions are rotating at the same speed, which would be synchronous speed, the differential gear cage stands still, but when there is a difference of speed between the synchronous speed of the synchronous motor and the speed of the induction motor, the rotation of the differential gear cage is a measurement of the number of revolutions slip.

(2) By means of the stroboscopic method, which employs a disk either painted on a paper glued to the end of the induction motor shaft or painted directly on the end of the shaft. This disk contains an equal number of equally spaced black and white sectors, the number of each being equal to the number of poles of the induction motor. When a neon light is attached to the same power system from which the induction motor is running and is allowed to illuminate the disk on the end of the induction motor shaft, the black sectors of the disk will appear to be standing still if the motor is running at synchronous speed, but if it is operating with slip, the black sectors of the disk will rotate backwards.

(20) The slip in rpm $= \frac{n_s}{P}$

where $n_s$ = number of black sectors passing a given point in one minute

* Wattmeter measurement.

P= number of poles of induction motor

(21) and the % slip=

$$\frac{\text{rpm slip} \times 100}{\text{synchronous rpm of induction motor}}$$

(3) By means of the slip beat, which is frequently quite pronounced in certain motors having two, four, and six poles and which can be distinguished by ear or a stethoscope attached to the motor frame. Since the motor makes this peculiar noise each time it slips a pole,

(22) the rpm slip=

$$\frac{\text{number of slip beats in 1 minute}}{P}$$

(4) By counting the beats of a d-c milli-voltmeter placed across the ends of the induction motor shaft. The rpm slip is determined from equation (22).

If a number of slip points can be taken, a curve of percent slip plotted against amperes input can be constructed as in Fig. 5. The curve obtained will provide a direct check on the rotor loss as determined by the graphical circle diagram method.

The kw rotor copper loss is

(23) $$R_{c1}=\frac{\text{hp output}\times 0.746\times \%\text{ slip}}{100-\%\text{ slip}}$$

(See equations (11) and (12)) or more accurately,

$$R_{c1}=\frac{(\text{hp output}\times 0.746+\text{kw windage and friction loss})\times \%\text{ slip}}{100-\%\text{ slip}}$$

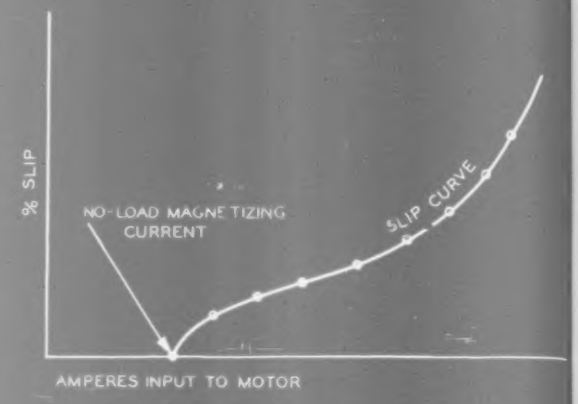
For squirrel cage and slip ring type induction motors, any of these three methods can be used for the determination of rotor copper loss. For a slip ring induction motor where loading is not possible and where the rotor resistance is known, the secondary current can be calculated from the circle diagram. The rotor copper loss is determined from the calculated current and the known resistance. In order to obtain the total rotor loss, which is a direct function of the slip, the brush contact drop loss must be added to the rotor copper loss.

Let $I_2a$= secondary current in terms of primary current as scaled from the circle diagram, as in Fig. 4.

$E_2$= secondary voltage at standstill taken directly from the induction motor nameplate.

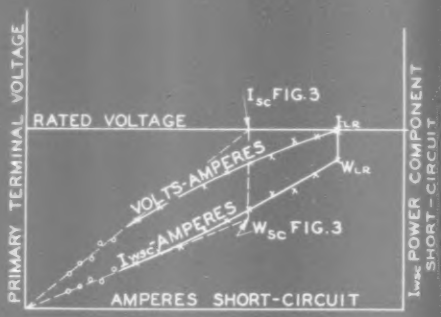
E = line voltage terminal to terminal taken directly from the induction motor nameplate.

$R_2$= the resistance of the rotor copper from one slip ring to another slip ring in ohms at 25° C.




SLIP AMPERE CURVE OF INDUCTION MOTOR

Fig. 5




○ TEST POINTS FOR UNSATURATED PART OF CHARACTERIS
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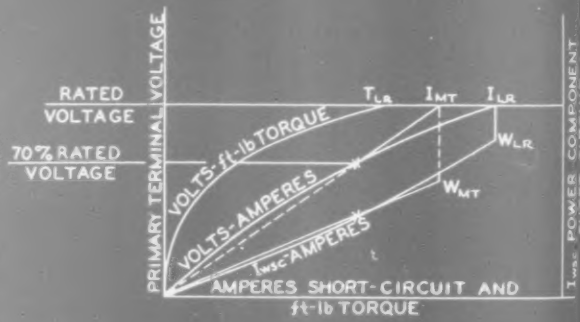
SHORT-CIRCUIT CHARACTERISTICS
SATURATED CONDITION

Fig. 6




STARTING TORQUE AND MAXIMUM TORQUE

Fig. 7

The current flowing in the rotor copper for any given load Oa, Fig. 4, in terms of primary current is $I_o a$, but in actual secondary amperes is

$$(24)\quad I_s = \frac{I_o a \times E}{E_2}$$

The kw rotor copper loss is

$$(25)\quad R_{c1} = \frac{1.5\, I_s^2\, R_s\, T_r\, k_r}{1000}$$

where $T_r$ = a factor greater than 1.0, depending on the temperature of the rotor copper. For simplicity $T_r$ should be taken as $T_s$. (See equations (6) and (7) ).

$k_r$ = a variable covering stray loss like $k_p$, equations (6) and (7).

Allowing one volt drop for each collector ring using carbon and graphite brushes, or one-quarter volt drop for each collector ring using metal graphite type brushes (both cases with pigtails attached),

the brush contact loss in kw for three slip rings is

$$(26)\quad B_c = \frac{I_s \times 3 \times 1 \text{ (or } 0.25)}{1000}$$

and the total kw rotor loss (for slip ring motors)

$$(27)\quad = R_{c1} + B_c$$

The rotor loss, particularly on squirrel cage induction motors, is sometimes difficult to determine with reasonable accuracy, because the short-circuit test introduces the problem of reading power input at very low power factor. As the rotor loss is a direct function of the slip, it is sometimes advantageous to be able to check the efficiencies obtained by the graphical circle diagram method against the segregated loss method, as the other losses are comparatively easy to obtain. This method, which should be in fairly close agreement with the circle diagram method, is in accordance with A. I. E. E. Standards No. 9 and is known as the "conventional efficiency method."

In the determination of efficiency, it must be considered that the temperature of the rotor will vary for each different load point; hence the copper loss will be a function of this varying temperature. As the rotor copper loss is affected, the slip would also vary with the temperature, and therefore the whole calculation becomes considerably involved. If the temperature and slip can be accurately determined for each load point, so much the better, but for the sake of simplification, it is reasonable to assume that the copper losses and slip at any and all load points are taken at a temperature of 75° C., as stated in the A. I. E. E. Standards No. 9 and the A. S. A. Standards C-50-1936.

The conventional efficiency by the segregation of loss method of an induction motor for any given load point such as "a," Fig. 4, can be put in tabulated form as shown in Table I.*

## • Interpretation of the circle diagram of the saturated motor

The effect of saturation is shown by Fig. 6. This is a similar motor to the one shown by the short-circuit curve, Fig. 3, except that in this case the motor is a saturated machine and the short-circuit test has been continued right on up to full voltage. It is seen that with the saturated motor the short-circuit saturation is a curve and not a straight line, and that the actual steady-state condition of starting current, if the motor were started directly across the line, would be $I_{LR}$ and not $I_{sc}$. It is important to note that the extrapolated straight line $I_{sc}$ even of the saturated machine checked against the actual load points of the circle diagram (Fig. 4) will determine the running performance of this type of motor from zero to approximately one and one-quarter to one and one-half times full load. Beyond this loading the saturated short-circuit line $I_{LR}$ determines the locked rotor current and the starting torque.

As a check on the graphically obtained locked rotor starting torque, it is desirable, but not absolutely necessary to have available the measurement of torque for each point of the short-circuit curve. If these measurements are obtained, the data can be plotted according to the form shown by Fig. 7. When the short-circuit current does not follow a straight line, it is important to note that the starting torque is not a function of $E^2$ but of $I_{LR}^2$ and the short-circuit current is not a straight line function of the line voltage E.

## • Maximum torque

In order to obtain empirically the maximum torque from the graphical method that will closely approximate that which might be obtained from an actual test, the points marked by crosses on the curves $I_{LR}$ and $W_{LR}$ of Fig. 7 that are at a short-circuit current corresponding to 70 percent of the rated voltage are used. From the origin draw straight lines through these 70 percent voltage points to intersect the rated voltage line at $I_{MT}$ and the vertical projection of $I_{MT}$ at $W_{MT}$. These points indicate the current and power component to be used in graphically determining the maximum torque from the circle diagram.

To determine the maximum torque circle, the maximum torque current $I_{MT}$, Fig. 8, is laid off using O as a center. A line is drawn parallel to OM at a distance $W_{MT}$ (from Fig. 7) above OM, intersecting $I_{MT}$ at $T_{MT}$. With the center of a compass

* Will appear with PART II.

on the line $I_oP$, a semicircle is scribed touching the two points $I_o$ and $T_{MT}$. The center of this circle is $C_{MT}$. This circle is used only for empirically determining the maximum torque of the motor.

The total copper loss, both stator and rotor, is represented (for the maximum torque circle) by $W_{MT}-I_W$. This may be divided into stator and rotor power component quantities by subtracting the stator copper loss from the total copper loss in a manner similar to that given in equations (5) and (6).

The rotor copper loss in power component amperes for the maximum torque circle current $I_{MT}$ is

(28) $R_{MT}=W_{MT}-I_W-S_{MT}$

where the stator copper loss in power component amperes is

(29) $S_{MT}=\dfrac{1.5\, I_{MT}^2\, R_p\, T_s\, k_s}{E\sqrt{3}}$

These respective points are laid off in the same manner as for the running circle diagram, and the corresponding loss lines $I_oT_{MT}$ and $I_oN_{MT}$ are drawn. From center $C_{MT}$ a line is drawn perpendicular to $I_oN_{MT}$ intersecting the maximum torque circle at "g."

(30) maximum torque in synchronous hp $=\dfrac{MT\times E\sqrt{3}}{746}$

where MT = the length of the power component amperes "gh" as scaled from the diagram Fig. 8.

## • Locked rotor

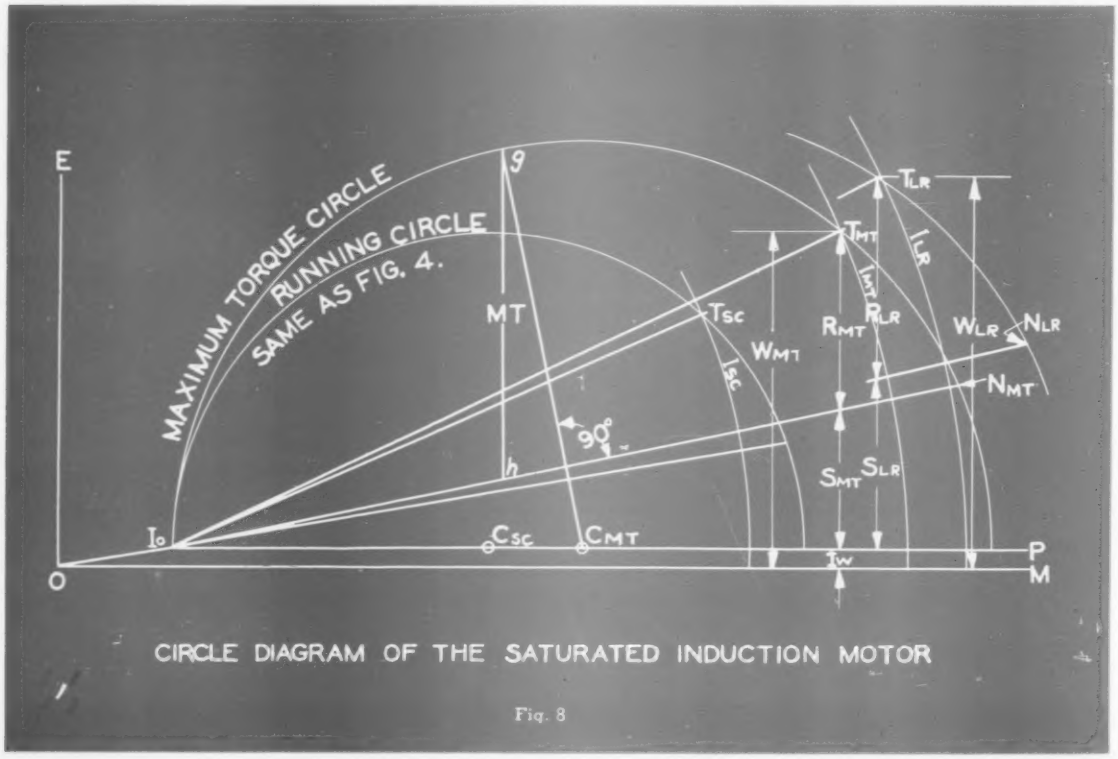
It is not necessary to draw the circle diagram for the locked rotor current $I_{LR}$. The main thing to be ascertained is the starting torque.

The stator $S_{LR}$ and rotor $R_{LR}$ copper losses are determined in the same manner as before and laid off as shown in Fig. 8. The locked rotor starting torque in synchronous hp

(31) $=\dfrac{R_{LR}\times E\sqrt{3}}{746}$

where $R_{LR}$ = power component amperes as scaled from the diagram Fig. 8.

In any such determination of the maximum torque and the locked rotor torque of the saturated machine by means of no-load tests, it is recognized that the speed-torque characteristics from the maximum torque point to the static locked rotor starting torque can be only approximated. A load test from zero speed to full speed, if it could be made and if great accuracy of the curve between these points were actually needed, would definitely establish this part of the curve.




CIRCLE DIAGRAM OF THE SATURATED INDUCTION MOTOR

Fig. 8

Fig. 1

# HYDRO POWER ON THE CHIPPEWA

• C. R. Martin
HYDRAULIC DEPARTMENT...ALLIS-CHALMERS MANUFACTURING CO.

• The Chippewa River with its early history and romance forms one of the very interesting parts of Wisconsin. Paul Bunyan stories are often associated with this territory because of its large trees, rugged country, fast-flowing rapids over which the logs were driven, and the adventuresome spirit required in the early lumbering days. Today this area has changed from a center of extensive lumbering operations to a farming, industrial, and resort country. The history of water power development on the Chippewa began in 1848 with the construction of a dam on one of its tributaries, the Red Cedar River, at Menominee, Wisconsin.

Flowing through the greater portion of the northwestern part of the state on its way to the Mississippi, this river with its tributaries has a drainage area representing 17 percent of the total area of Wisconsin and covering over six million acres. Fig. 2 is a map of the entire drainage area of the Chippewa River.

The power-producing section of the river has a drainage area of about 4,800,000 acres and has an average runoff of about 5,000,000 acre-feet. Industrial and utility interests have now constructed reservoirs to retain about 10 percent of this runoff in order to increase the low flow during the summer and winter seasons for power-producing purposes. These power-producing dams with their reservoirs are of great value to the general public because of the more adequate water supply that makes these streams more usable and attractive.

The water level in the upper reaches of the river is at an elevation of about 1600 ft above sea level. This level drops 920 ft in its descent to the Mississippi River. The sediment carried down the Chippewa has so obstructed the flow in the Mississippi River that a partial dam has been formed and Lake Pepin created.

Of this total drop, 415 ft is used in developing hydro-electric power, 100 ft in drawdown at the storage reservoirs, and the remaining 405 ft for the most part represents a gradual drop in the upper reaches of the tributaries.

The tabulation on page 17 lists the various hydro-electric plants and storage reservoirs now in service.

Fig. 3 is a U. S. Geological Survey map showing the Chippewa Falls area where the Chippewa Falls and Wissota Plants of the Northern States Power Company are located (see Area B on drainage map). The airplane view, Fig. 1, of the Chippewa Falls Hydro Plant with Wissota Lake in the background at the point marked "X" and the closeup air picture, Fig. 4, of the same plant show the latest hydroelectric plant installed on the Chippewa River. Six 5000 hp hydraulic turbines are installed at this plant, and the Wissota Plant, Fig. 5, has six 5500 kw hydroelectric units. This view also shows the outdoor transformer and switching station. Wissota is one of the two largest hydroelectric plants in Wisconsin. The only comparable installation in size is the Prairie du Sac Plant of the Wisconsin Power and Light Company.

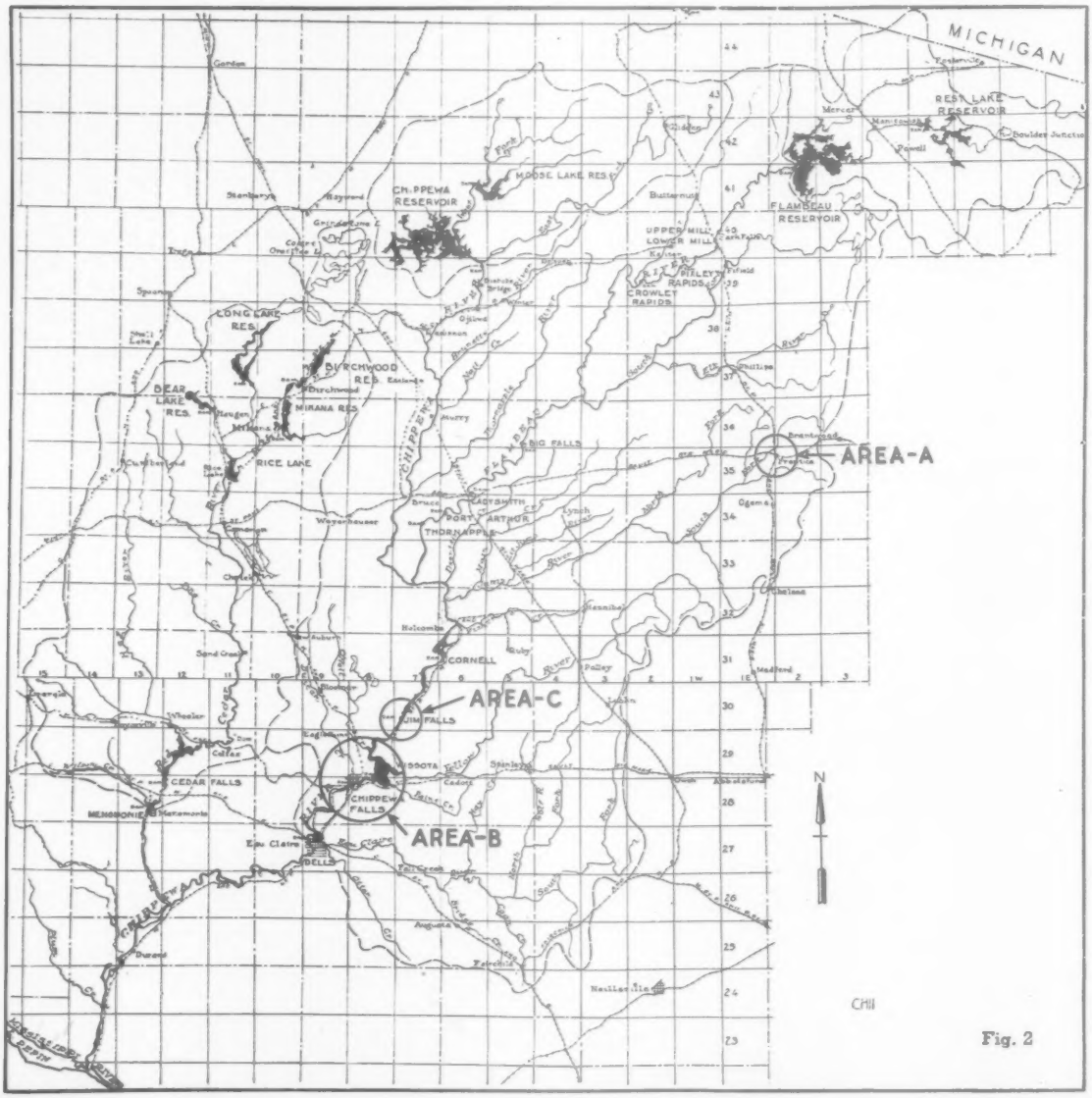



Fig. 2

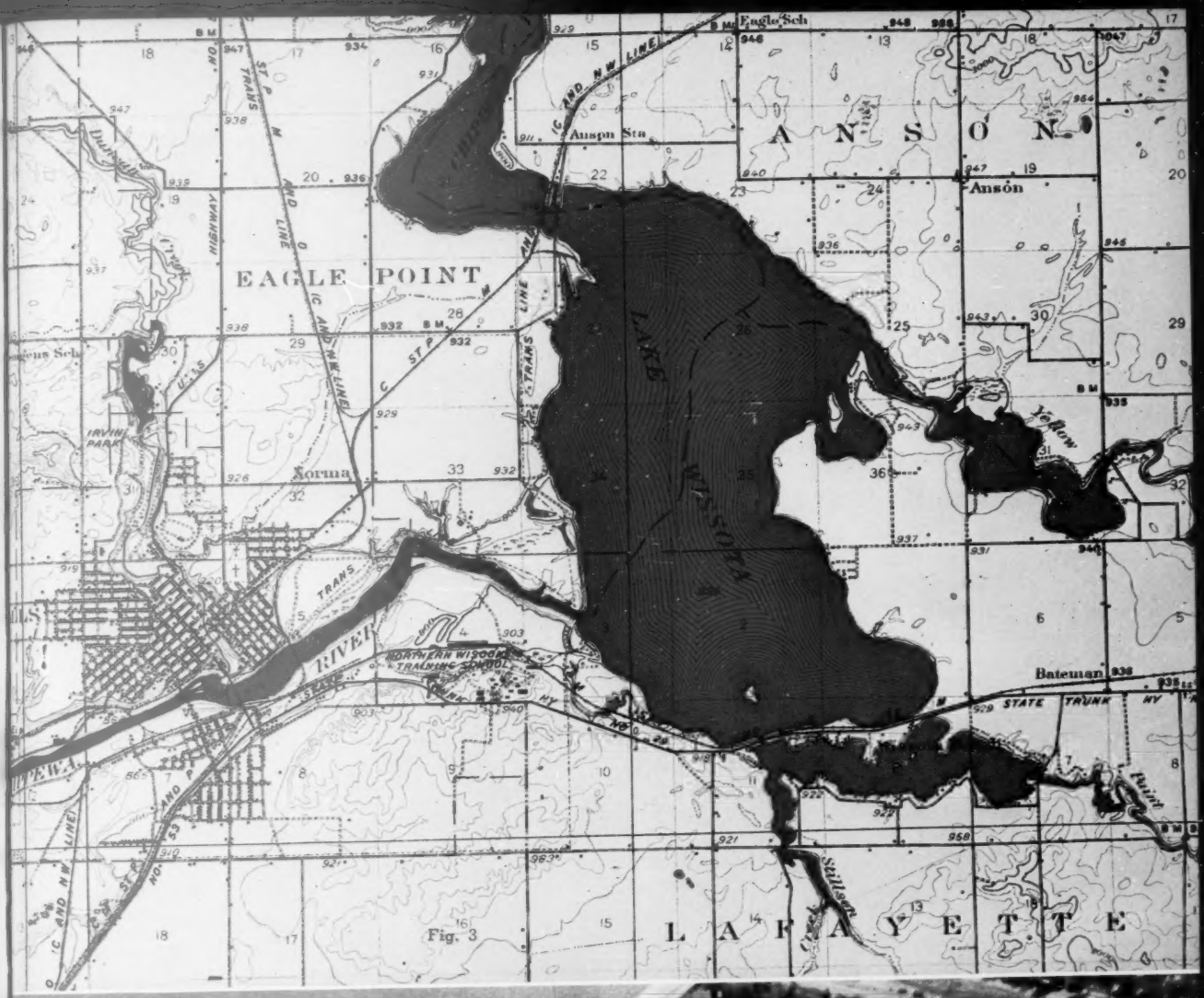

EAGLE POINT
LAKE WISSOTA
A N S O N
L A F A Y E T T E
Anson
Ansn Sta
Eagle Sch
Bateman
Xorma
RIVER
STATE TRUNK HY
IC AND NW LINE
ST P TRANS LINE
HIGHWAY
IRVING PARK
Point
Stillson

Fig. 3

Fig. 4

Fig. 5

Figure 6 is a view from the air of the hydroelectric plant at Jim Falls, Wisconsin, which is shown as Area C on the drainage map. This plant contains three 5000 hp hydroelectric units.

The three plants, Figs. 1, 4, 5, and 6, are the largest installations in the Chippewa drainage area. Each plant, while different in general arrangement, has one common property, namely, that it is located out of the main stream channel. At the Chippewa Plant, the powerhouse serves as part of the dam, but the spillway section is placed in direct line of the stream. Heavy ice flows can be discharged through the spillway section of the dam without endangering the operation of the hydraulic turbines. The spillways of the Wissota installation are located some distance from the hydro station, and ice congestion is avoided in this way. The Jim Falls layout has a canal which leads from the dam to the powerhouse, and the ice is by-passed over the dam by means of a boom placed across the intake to the canal.

An interesting ice formation at the Chippewa reservoir is shown in Fig. 7. Formations of this kind are due to the freezing of the spray rising from the water discharged underneath the gate. This spray starts freezing first on the pier walls and gradually accumulates until it completely spans the opening and forms a dam across the opening with only the space at the waterline for passing the water. This difficulty can be avoided by the use of a modern, long-span roller gate.

## WATER POWER PLANTS

| No. | Name of Plant | River | Owner | Date Orig. Const. | Drainage Area Sq Miles | POWER PLANT DATA | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Normal Head Feet | Number of Units | CAPACITY | |
| | | | | | | | | cfs | kw at 80% pf |
| 1 | Cornell | Chippewa | Northern States Power Company | 1911 | 4,797 | 38 | 2 | 5,500 | 2,160 kw |
| 2 | Jim Falls | Chippewa | Chippewa Power Company | 1910-1923 | 4,891 | 55 | 3 | 3,500 | 14,400 kw |
| 3 | Wissota | Chippewa | Northern States Power Company | 1917 | 5,548 | 57 | 6 | 10,000 | 31,680 kw |
| 4 | Chippewa Falls | Chippewa | Northern States Power Company | 1928 | 5,555 | 29.6 | 6 | 12,500 | 21,600 kw |
| 5 | Dells | Chippewa | Eau Claire Development & Improvement Company | 1877 | | | 6 | | 8,900 kw |
| | | | Northern States Power Company | 1924 | 5,752 | 27 | 1 | 5,300 | 600 kw |
| 6 | Rice Lake | Red Cedar | Northern States Power Company | 1864 | 410 | 12 | 2 | 380 | 320 kw |
| 7 | Cedar Falls | Red Cedar | Northern States Power Company | 1910 | 1,667 | 52 | 3 | 2,400 | 6,000 kw |
| 8 | Menominee | Red Cedar | Northern States Power Company | 1848 | 1,761 | 21 | 2 | 1,200 | 1,200 kw |
| 9 | Upper Dam | Flambeau | Flambeau Paper Company | 1895 | 720 | 17 | 3 | 1,050 | 1,950 hp |
| 10 | Lower Dam | Flambeau | Flambeau Paper Company | 1895 | 725 | 18 | 3 | 1,000 | 1,800 hp |
| 11 | Pixley Rapids | Flambeau | Flambeau Paper Company | 1916 | 740 | 21 | 3 | 970 | 2,650 hp |
| 12 | Crowley Rapids | Flambeau | Flambeau Paper Company | 1930 | 800 | 21 | 2 | 1,340 | 2,700 hp |
| 13 | Big Falls | Flambeau | Lake Superior District Power Company | 1920 | 1,900 | 52 | 3 | 2,700 | 12,000 hp |
| 14 | Ladysmith | Flambeau | Lake Superior District Power Company | 1899 | 1,960 | 16 | | 2,200 | |
| 15 | Port Arthur | Flambeau | Lake Superior District Power Company | 1908 | 1,970 | 18 | | 2,100 | |
| 16 | Thornapple | Flambeau | Lake Superior District Power Company | 1912 | 1,980 | 12 | | 2,000 | |
| 17 | Colfax | Red Cedar | Wisconsin Hydro-Electric Company | | 1,100 | 21 | | | 2,000 hp |

## STORAGE RESERVOIRS

| No. | Name of Reservoir | River | Owner | Date Orig. Const. | DRAWDOWN, FEET | | | STORAGE | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Maximum Possible | Agreed Regulation | | Area Full, Acres | Capacity | |
| | | | | | | Winter | Summer | | Acre Feet | Million Cu Ft |
| 18 | Moose Lake | W. Fork Chippewa | Chippewa & Flambeau Improvement Company | 1875 | 9.2 | 7.0 | 0 | 1,800 | 8,750 | 380 |
| 19 | Chippewa (PK) | Chippewa | Northern States Power Company | 1923 | 26.0 | 21.0 | 21.0 | 15,300 | 223,000 | 9,700 |
| 20 | Rest Lake | Manitowish | Chippewa & Flambeau Improvement Company | 1887 | 7.5 | 3.5 | 1.25 | 4,200 | 15,200 | 660 |
| 21 | Flambeau | Flambeau | Chippewa & Flambeau Improvement Company | 1926 | 22.0 | 15.0 | 15.0 | 17,800 | 126,500 | 5,500 |
| 22 | Haugen (Bear Park) | Bear Cr. | Northern States Power Company | 1879 | 6.8 | 4.8 | 4.8 | 2,055 | 6,400 | 279 |
| 23 | Long Lake | Brill | Northern States Power Company | 1883 | 7.4 | 3.7 | 2.2 | 3,950 | 11,300 | 493 |
| 24 | Birchwood (Birch Lake) | Red Cedar | Northern States Power Company | 1882 | 12.5 | 6.5 | 4.5 | 3,400 | 13,900 | 605 |
| 25 | Mikana (Cedar Lake) | Red Cedar | Northern States Power Company | 1882 | 7.0 | 5.0 | 3.0 | 2,800 | 11,500 | 500 |

Fig. 6

Fig. 7

OR FOLLOWING PAGES
Dismantling one of four 72-inch sewage pumps for shipment.

SANITARY DIST
OF CHICAGO
A

# RECTIFIERS IN REVERSE

D. Journeaux
PATENT ATTORNEY . . . ALLIS-CHALMERS MANUFACTURING CO.

● Of recent years, the mercury arc rectifier has been the object of so many descriptions that its action is becoming taken for granted. All who can read may learn that the rectifier is a device conducting electric current in only one direction. And it now seems quite natural that a rectifier connected in series with a source of alternating current and with a load should act as a check valve and transmit direct current from the source to the load.

When, however, it is proposed to use a rectifier for causing a source of direct current to deliver alternating current to a load, the reader may believe that his credulity is being abused. Yet such conversion of direct current into alternating current, or "inversion," takes place in every stage of "amplification" of every radio receiving set. In power circuits, however, it is necessary to utilize a mode of action differing in details from that of radio circuits.

## ● Rectifier capable of reversal

Nevertheless, it seems strange at first blush that the power transmitted through a rectifier should be capable of reversal, since the rectifier's first duty is to prevent any reversal of current. This thought is evidently fostered by our general use of constant voltage circuits in which a reversal of power flow can be obtained only by a current reversal. We have thus been led to forget that it is just as effective—if otherwise permissible—to reverse the power flow by reversing the voltage while leaving the direction of the current flow unchanged. Since the usual polyphase rectifier circuits are somewhat complicated, it may be desirable first to follow this reversal in simpler circuits even if such circuits are without practical application.

Let the circuit represented in Fig. 1 be first considered comprising a d-c generator G feeding a d-c motor M through a line without appreciable resistance and through a rectifier R. The current flow through the rectifier takes place with the usual voltage drop $E_R$, which may be considered as being constant. If the generator—which may be part of a Ward-Leonard set, for example — is excited to generate current under a terminal voltage $E_G$ higher than the motor voltage $E_M$, the flow of energy will be from the generator to the motor, the current flowing through the circuit in the conventional direction indicated by the arrows. If the potential of the grounded lower conductor is taken as the point of reference, the potential along the upper line conductor is of positive polarity and follows the voltage diagram shown in Fig. 1.

Let the system next be considered in the condition illustrated in Fig. 2. The excitation current of the generator has been reversed and decreased, and the excitation current of the motor has likewise been reversed but increased. If the motor is driven as a generator by the momentum of its load without reversing its direction of rotation, current will continue to flow in the same direction as in Fig. 1, but the transfer of energy will be reversed. The erstwhile generator will operate as a motor, and means should be provided to absorb the mechanical energy available at its shaft. The potential of the upper conductor then follows the voltage diagram of Fig. 2 and is negative from one end of the line to the other. The rectifier anode is thus at a nega-

tive potential but its cathode is at a still more negative potential so that the flow of current through the rectifier may take place as usual from anode to cathode.

If the two machines of Fig 1 are next assumed to be of the synchronous a-c type, during the voltage half-cycles rendering the upper conductor positive (or positive half cycles), the current and rms voltage conditions are again as shown in Fig. 1 (as when the machines are of the d-c type). A composite oscillogram of the generator voltage $E_G$, the motor voltage $E_M$, and the line current I will then be about as shown in Fig. 3, at least if the total inductance of the circuit is relatively low. During the intervening or negative half-cycles, the current tends to reverse but is prevented from doing so by the rectifier. The current flow between the two machines is accordingly uni-directional and pulsating.

With a-c machines, to reverse the flow of energy it is evidently not necessary or even useful to reverse the excitation currents. If the generator excitation is decreased and the motor excitation increased, during the positive half cycles of the voltage, the current tends to flow in the non-conductive direction of the rectifier, which opposes its passage. During the negative half cycles the voltage and current conditions are as represented in the voltage diagram of Fig. 2, but the composite oscillogram of Fig. 3 is modified, as shown in Fig. 4. Current flows while the two voltages are negative and may pass freely through the rectifier since the cathode is more negative than the anode.

## • Rectifier serves as commutator

In the examples considered above, the rectifier is really superfluous, but if the generator is of the a-c type and the motor of the d-c type, the rectifier becomes indispensable. The rectifier may be considered as serving as a commutator for making a d-c machine out of the a-c generator. Looking at it from another angle, the rectifier permits current to flow between the two machines during the half cycles in which the machine electromotive forces are of comparable magnitudes and are directed in opposition in the circuit, as is necessary in power transmission systems. The rectifier also prevents the flow of current during the half cycles in which the machine electromotive forces are additive in the circuit and tend to put the system in short-circuit condition.

Considering the circuit when the flow of energy is from the generator to the motor, the oscillogram of the machine voltages and current assumes the aspect shown in Fig. 5. The back emf $E_M$ of the motor may be considered as constant, and current flows between the machines during the portion of the positive half cycles in which the generator voltage is higher than the motor back emf plus the rectifier arc drop $E_R$. During the negative half cycles, the rectifier prevents the reverse flow of current.

## • Action of grid control

We have so far considered that the rectifier was simply a unilateral conductor, in which the selective conductivity or "valve action" is obtained solely by making the anode of material capable of collecting electrons but incapable of emitting many under the operating conditions of the rectifier, while the cathode is of a material which may indifferently emit or collect electrons when placed in the proper working condition.

In modern rectifiers, however, it is generally preferred not to rely altogether on the valve action of the anode. This action is placed under the control of a kind of pilot anode shaped as a grid and placed in the arc path of the rectifier. When it is maintained at a positive potential with respect to the cathode potential, the grid attracts electrons toward itself and toward the anode. When it is at a negative potential, it repels the electrons away from the anode. The grid thus acts as an electron chaser for the anode.

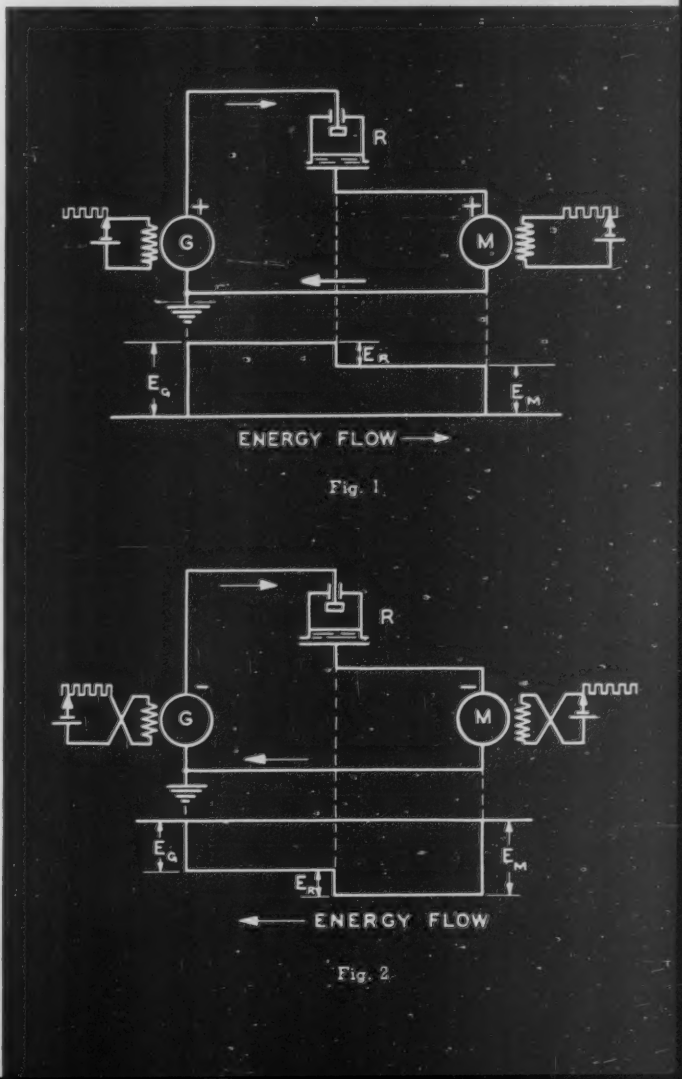



Fig. 1




Fig. 2

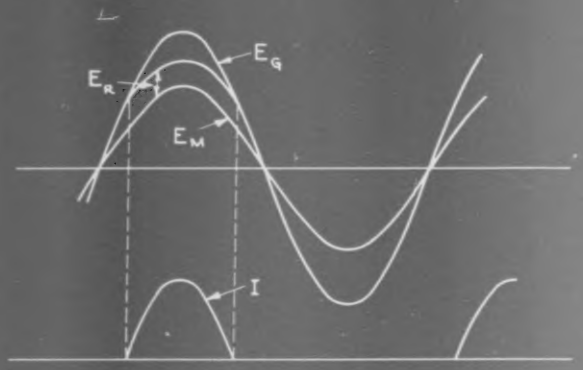



Fig. 3

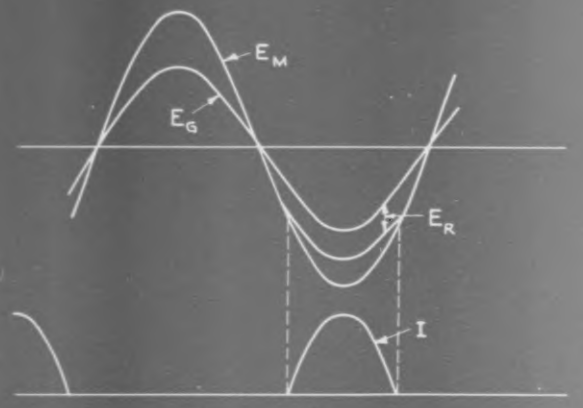



Fig. 4

As the valve action of the anode is nevertheless always present, the anode cannot pick up current as long as at least the anode or the grid is negative but will pick up current as soon as the grid has become positive and the anode also has become more positive than the cathode by at least the amount of the arc drop.

There are numerous ways of controlling the grid potential. For example, the grid may be connected with the cathode through the secondary winding of a transformer excited from generator G and through a battery as illustrated in Fig. 6. The polarity of the transformer is such that the grid is already positive when the anode becomes positive as represented by curve $E_g$ in Fig. 5. The grid thus introduces no change in the operation of the system but only renders the operation of the rectifier more certain.

If the grid transformer voltage is retarded by 180°, as shown in Figs. 7 and 8, the grid and the anode are never simultaneously positive with respect to the cathode; and, other conditions remaining the same, the rectifier cannot transmit any current. If the motor is then driven by the momentum of its load, its excitation may be reversed and increased to depress the cathode potential to the neighborhood of the negative peak of the generator voltage wave.

The anode is then positive with respect to the cathode during most of the voltage cycle and can pick up current as soon as the grid becomes positive. A current impulse is then initiated from the motor (acting as a generator) to the generator (acting as a motor) and is terminated when the anode is no longer more positive than the cathode by at least the value of the arc drop. Such current impulses are thus transmitted during every cycle when the motor and generator voltages are closely enough matched to limit the current to whatever value may be desired. The transmission of power has been reversed without current reversal by reversing the voltages under which the current flow takes place.

## • Polyphase system

The system of Fig. 7 may be considered as not being a true inverting system, since it transmits uni-directional impulses between the machines instead of converting direct current into alternating current. A true inverting system may be obtained, however, by joining the generator with the motor as illustrated in Fig. 9. This arrangement differs from the well-known rectifying systems used for electric traction and in electrolytic plants mainly by the phase relation between the anode and grid voltages and by the polarity of the d-c circuit.

The system consists, in effect, of six systems of the type shown in Fig. 7, as may be seen by following the six anode circuits separately. The six rectifiers required are replaced by a single six-anode rectifier to simplify the drawing, but six separate single-anode rectifiers could be used just as well. A transformer is used to obtain three-phase alternating current by induction from the current impulses transmitted through the six anodes at intervals of 60 electrical degrees.

As the anode current impulses overlap, the current taken from the regenerating motor is a fairly uniform direct current. Of course, the source of direct current need not be a regenerating motor, and a system as illustrated in Fig. 9 may be used to operate continuously as an inverter receiving current from any d-c generator. Alternating current may also be converted into direct current by a rectifier and supplied through a transmission line to an inverter which reconverts it into alternating current.

In this manner d-c transmission of power may be effected under conditions which may render it more economical than a-c transmission for certain ranges of power transmitted and of length of line. This arrangement can also be used as a convenient system of frequency conversion, as the frequencies of the a-c circuits connected to the rectifier and to the inverter need not be equal nor even in any particular ratio.

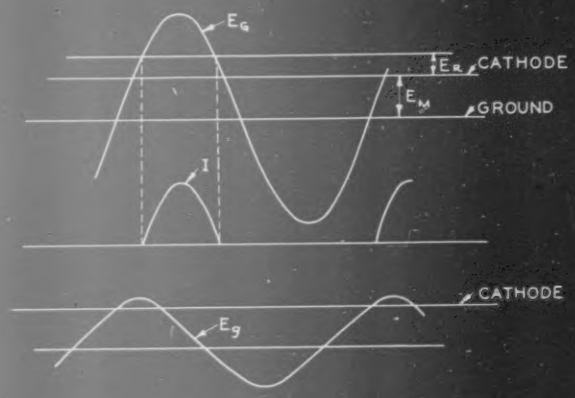



Fig. 5

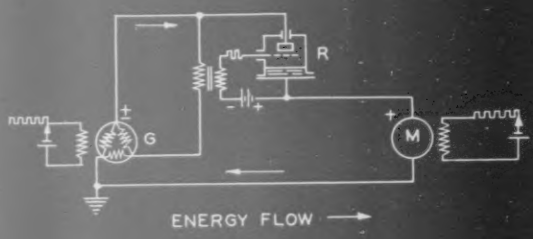



Fig. 6

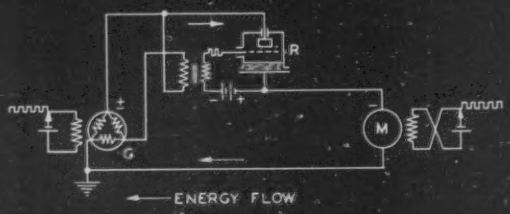



Fig. 7

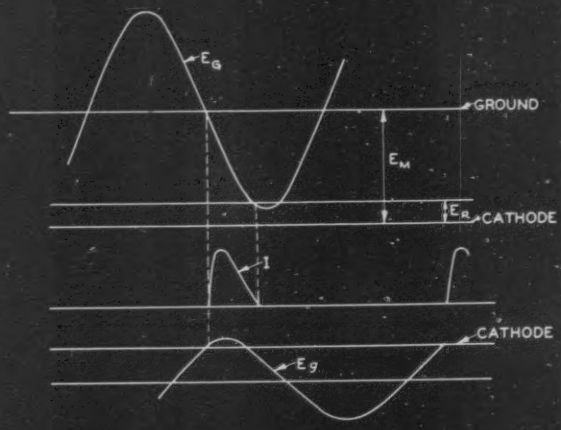



Fig. 8

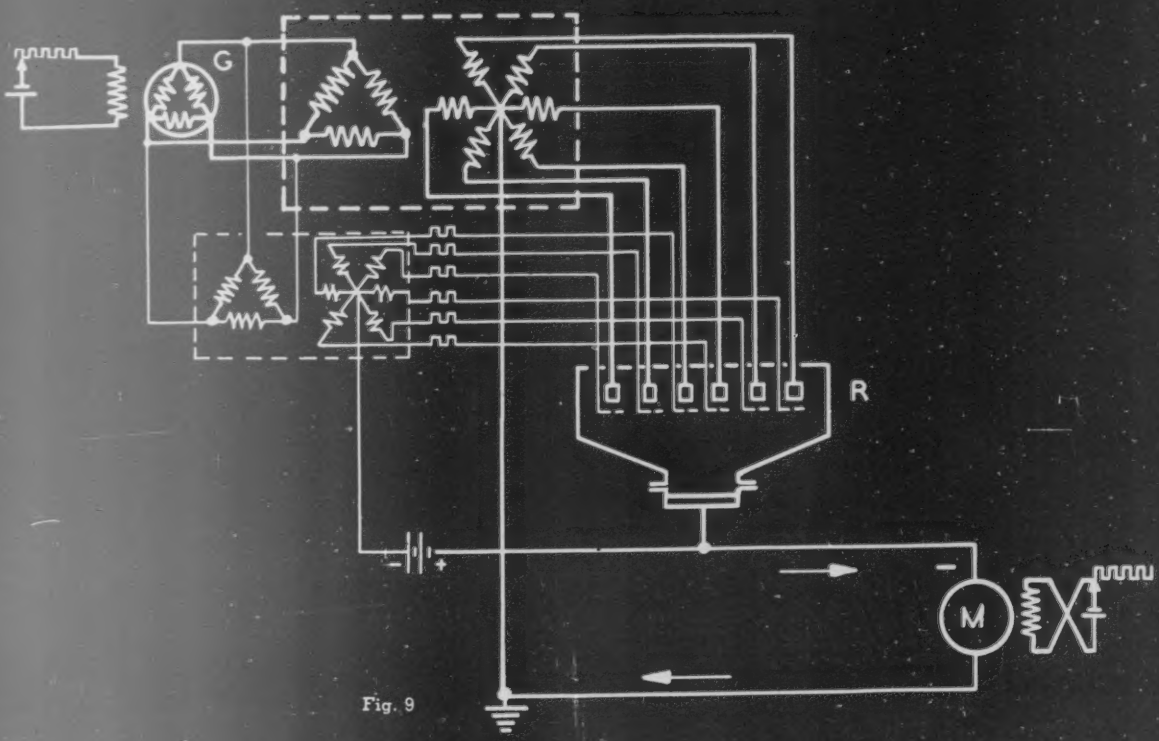



Fig. 9

# A MERCURY ARC STATIC INVERTER

• S. R. Durand
RECTIFIER DIVISION . . . ALLIS-CHALMERS MANUFACTURING CO.

● Because a mercury arc power rectifier is essentially a valve device for limiting the flow of current to one direction, it is generally considered to be useful only for the conversion of alternating current into direct current power. However, this conception is erroneous, for the direction of power flow through a converting unit can be changed about by reversing the voltage instead of the current; and modern mercury arc converters can thus be regulated by grid-control to accomplish inversion of direct current into alternating current power.

Various methods of controlling the operation of static inverter equipment have been used, but all methods require a reversal of the voltage across the inverter unit instead of a reversal of the d-c current as commonly employed in changing over rotating equipment for inverter service. The direction of d-c current flow in a rectifier and inverter is the same as indicated by arrows in the elementary circuit diagram of Fig. 1; the d-c terminal voltage across the static converter units is reversed, as shown by polarity markings.

AT LEFT: Machining an hydraulic turbine runner.

Rectification of power from an a-c supply system to a d-c load circuit is accomplished by an inherent property of a mercury arc in vacuum, namely, that an arc current when not influenced by grid-control will be commutated periodically from each anode carrying the current to the succeeding anode in the firing sequence when this anode receives in turn the highest positive a-c potential. The current permitted to flow through the

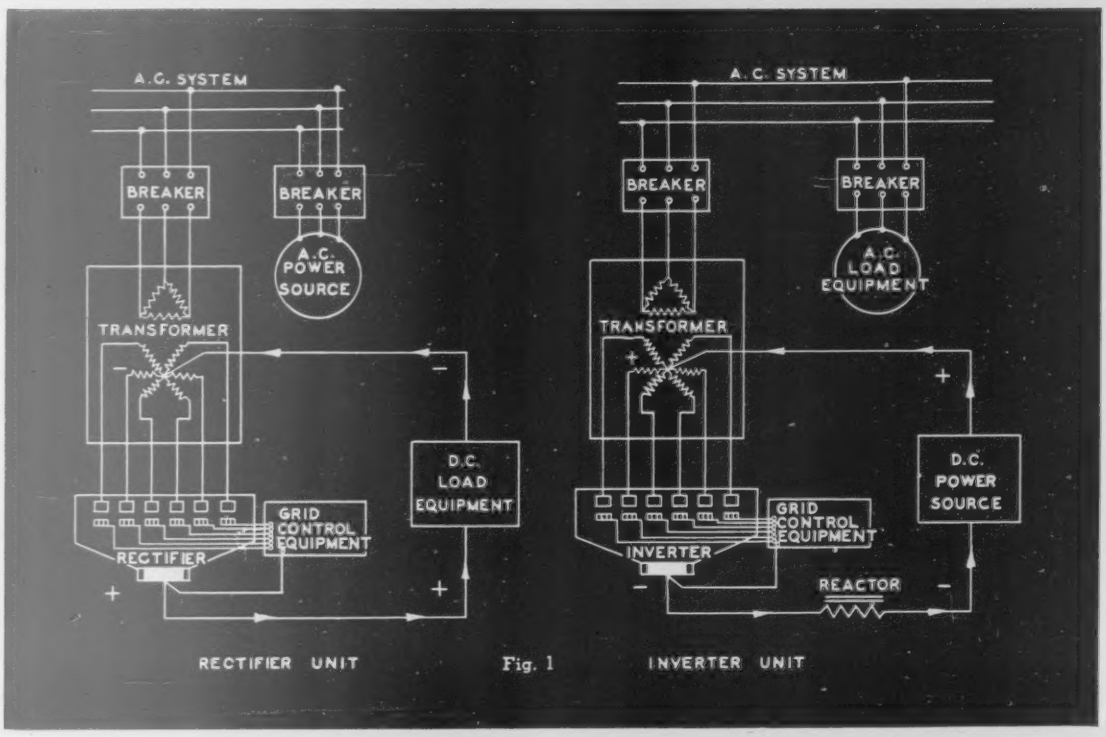



Fig. 1

Fig. 2

rectifier unit is thus effectively limited to a series of uni-directional impulses which are combined to produce the d-c current in the load circuit.

Inversion of power from a d-c supply system into an a-c load circuit cannot be accomplished by any inherent property of a mercury arc in vacuum but must be attained by controlled firing of the arc current in the inverter unit. The d-c current supplied to the inverter is effectively broken up into uni-directional impulses, and these impulses in flowing through the secondary phase windings of the transformer in successive order transmit a-c energy through the primary windings into the a-c power system.

## • Operation

A series of diagrams illustrating rectifier and inverter operation in relation to the a-c sinusoidal voltage waves impressed upon the anodes of a six-phase mercury arc converter is shown in Fig. 2.

Part (A) illustrates normal rectifier service in which the arc current is commutated from each anode in turn to the anode of the succeeding phase as the impressed a-c voltage of this phase becomes more positive than that of the phase carrying the arc. Commutation of arc current between two phases is not completed instantly, but an "overlapping" period occurs in which both anodes carry current simultaneously. The duration of the overlapping period is dependent, among other things, upon the inductance of the two transformer phases between which the current is transferred and upon the magnitude of the load current to be commutated. During the overlapping period, a voltage midway between the two phase voltages is attained; at the end of this period, the arc current is transferred entirely to the anode at higher voltage.

Part (B) illustrates rectifier operation with grid-control regulation in which the arc is not permitted to be established on each anode until a delayed point on the impressed a-c voltage wave. Delayed ignition is accomplished by maintaining a negative blocking potential on each grid in relation to the cathode until the desired firing point is reached, at which instant a positive potential is applied to release the anode.

In diagram (C) the angle of delay has been increased to a point where the arc current flows during an equal portion of each positive and negative part of the a-c voltage wave. The mean value of the voltage across the d-c circuit is reduced to zero.

As previously mentioned, the d-c voltage across a mercury arc inverter must be reversed with respect to that for rectifier operation in order to accomplish a return of power to the a-c system.

This can be done either by interchanging the connection or reversing the shunt field of the d-c machine so that it will function as a generator to supply d-c power to the inverter unit.

Part (D) of Fig. 2 shows an adjustment for inverter operation in which each anode is released during the time that a negative a-c transformer potential is impressed upon it. However, at the instant each anode is released by its grid, the positive d-c potential supplied by the generator through the neutral point of the transformer exceeds the negative a-c counter emf phase voltage supplied by the transformer. Therefore, the resultant potential on the anode is actually positive, and an arc current will be established. An overlapping period takes place in the same manner as in rectifier operation and persists until the arc current has been entirely transferred from the anode originally carrying current to the succeeding anode in the firing sequence.

During the firing period of an anode, the counter emf transformer phase voltage increases in value so that at the end of the firing period a greater differential in voltage exists between the d-c generator voltage and the a-c potential impressed on the succeeding anode in the firing sequence than between the d-c generator voltage and the anode carrying the arc. Therefore, when the succeeding anode is released by its grid, commutation of the arc current will occur; and the one with the greater differential in voltage will take over the current.

Part (E) of Fig. 2 illustrates another adjustment for inverter operation in which the anodes are released at a relatively later point on their respective a-c negative voltage waves. During commutation of the arc current between phases, the d-c voltage must be maintained substantially constant. This can be accomplished by introducing inductive reactance, and so for inverter service it is generally necessary to provide an air-core reactor in the d-c circuit.

## • Short-circuit point

It is apparent from the diagrams illustrating inverter operation that, after the a-c voltage on an anode carrying current has passed through its negative peak value, it becomes less negative and approaches a point where it will intersect and become equal to the voltage of the succeeding phase. The anode to take current must always be released by its grid before the negative a-c voltage impressed upon it has become equal to the a-c voltage of the anode carrying current; otherwise it will not have a greater positive differential voltage, and the arc current will not be transferred to it. In fact, the anode to take current must be released long enough in advance of this "short-circuit" point to permit commutation to be entirely completed before the a-c voltages become equal.

In case the arc is not completely transferred from one anode to the next before the short-circuit point, the differential voltage on the anode originally carrying current becomes greater in value than that on the other anode. Under this condition, the arc will be maintained on the original anode as the a-c phase voltage becomes less negative and eventually positive, so that a short circuit will be established across the d-c circuit and protective equipment will have to function to remove power.

## • Deionization time

Even though the arc current is successfully transferred between anodes before the short-circuit point, there is still a possibility that an arc may be re-established shortly beyond this point on the anode which originally carried current if the space around this anode is not quickly deionized. The design of the grids is important since they have a considerable influence in accelerating the deionization of the mercury vapor and thus gaining blocking control of the anodes in a very short interval of time. The deionization time of a modern mercury arc converter is so short and the grid blocking action so reliable that the chances of failure due to re-ignition beyond the short-circuit point is quite remote in units operating under normal conditions.

## • Ignition angle

The maximum voltage variations of the d-c power supply and a-c load systems must be considered in choosing the normal ignition angle of an inverter since a rise in the d-c voltage or a drop in the a-c voltage results in an increase of load current with a resultant longer overlapping period. The ignition angle must be set sufficiently far in advance of the short-circuit point to insure that commutation will be successfully completed during the highest load swings that may normally be expected to occur on the inverter system. The short-circuit point, deionizing time, ignition angle, etc., are designated on the diagram of Fig. 3.

## • Wave shape

Since the anodes of a mercury arc rectifier or inverter effectively draw square blocks of current during their firing periods, the wave shape of the a-c primary current is non-sinusoidal. This wave shape can be analyzed and broken down into fundamental and harmonic sinusoidal components. In the case of a rectifier operating at the natural firing period of the anodes, the fundamental and harmonic components are in phase with the voltage. When grid control regulation is applied, however, the fundamental and harmonic components are displaced with respect to the voltage.

The fundamental component can be resolved into a power component in phase with the voltage and a reactive component 90° out of phase. The wattless component consists of both the reactive component and the harmonic component and is equal to the vectorial sum of these two components. It is evident that grid control regulation of a mercury arc converter results in a larger consumption of wattless power, and it is desirable, therefore, to operate with as small an angle of regulation as possible.

## • Power factor

The power factor of a six-phase rectifier operated without grid control regulation may be as high as 0.95; it is less than unity on account of the wave shape distortion introduced into the a-c system. The power factor of a rectifier is always lagging. Regulation by means of grid control causes a decrease in the power factor in proportion to the cosine of the angle of delay. Because of the relatively high initial power factor obtained with a rectifier, it is usually possible to apply a moderate amount of grid control regulation when essential for adjusting the load.

An inverter must always be regulated by grid control so that its power factor cannot be as high as that of a rectifier operated at the natural firing period of the anodes. In order to maintain a relatively high power factor by keeping the wattless power component at a minimum, the ignition angle of an inverter must not be set further in advance of the short-circuit point than is absolutely necessary to insure stable operation under the most adverse load conditions normally expected to occur on the inverter system.

Because current flows to the anodes of an inverter in advance of the phase voltages supplied by the a-c system, an inverter delivers power at a leading power factor. However, it is obvious that the reactive power requirements of the inverter and of the a-c load equipment cannot be supplied from the d-c power source through the inverter, since it is impossible to obtain a quadrature voltage component from a d-c potential. The reactive power requirements of the inverter as well as of the load equipment can only be obtained from synchronous capacity connected to the a-c system. For this reason the addition of an inverter to an a-c system will not result in an improvement of the power factor, but, on the contrary, additional reactive power will be required of the a-c synchronous machines on the system, so that the power factor will actually become worse instead of better.

## • Efficiency

The efficiency of an inverter is comparable to that of a rectifier. Since the arc drop loss may range from about 15 volts to 30 volts, depending upon the load current and length of the arc path, the effi-

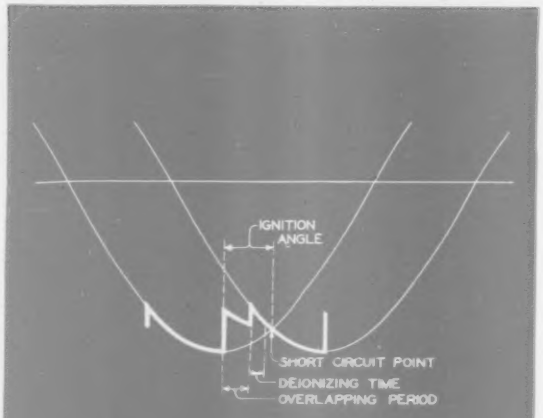



Fig. 3

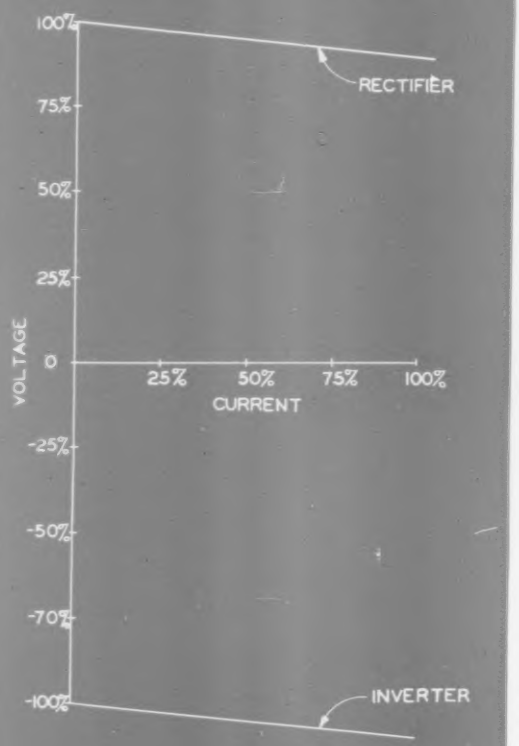



Fig. 4

ciency of a unit operating at 250 volts direct current will not be so good as one operating at a higher voltage. As the efficiency remains relatively high over a wide load range from very light load to full load, a static inverter of this type possesses distinct advantages in comparison to rotating equipment when the average load will be somewhat less than the full load rating of the equipment. Grid control regulation does not increase the losses in the inverter unit or in its transformer, and, therefore, the efficiency is not appreciably affected by adjustment of the ignition angle within the normal range of regulation.

## • Frequency determination

When an inverter is connected to supply power to an existing a-c power system, the frequency of the synchronous generators on the system will automatically determine the frequency at which the inverter will operate. When it is desired to supply a-c power to a load circuit that cannot be connected to an existing a-c system, it is essential to supply a synchronous machine with the inverter for determining the frequency and supplying the reactive power requirements of the inverter and the a-c load equipment. This machine can be coupled to a d-c motor and brought up to the desired speed by connection to the d-c power supply system. Besides determining the frequency and supplying the reactive power requirements of the a-c circuit, the synchronous machine also serves to supply harmonic frequencies necessary for improving the a-c wave shape.

## • Voltage regulation

In designing mercury arc rectifier or inverter plants to meet the requirements for interconnection between a-c and d-c systems, consideration must be given to the voltage changes caused by reactance drop due to overlapping between transformer phases, arc drop in the converter unit, and resistance drop in the transformer windings. When a mercury arc converter is operated as a rectifier, all of these voltage drops must be subtracted from the average value of the d-c no-load voltage to determine the output voltage under load conditions.

Since each of these voltage drops increases with an increase in load current, the regulation curve of a rectifier has a straight line slightly drooping characteristic. The average value of the rectified d-c output voltage cannot be raised unless the a-c input voltage to the rectifier transformer is increased in value or the transformer ratio is changed by means of tap control.

During inverter operation the voltage drops due to overlapping, arc loss, and resistance loss effectively add to the no-load values of the counter emf transformer phase voltages because the d-c supply voltage must overcome all of these voltages in order to force current to flow. Since the voltage drops that must be added to the counter emf transformer voltages effectively increase with increase in load current, an inverter possesses a straight line rising voltage regulation characteristic.

Fig. 4 illustrates typical voltage regulation characteristics of a rectifier and of an inverter. Each of these characteristics can be modified, if desired, by means of an automatic regulator controlling the ignition points of the anodes so as to obtain a flat or even an over-compounded characteristic. In the case of a rectifier, the automatic regulator would have to function to retard the ignition point at no-load and automatically decrease the angle of retardation as the load current increases in value. In the case of an inverter, the regulator would have to function to advance the ignition point at full load and automatically decrease the ignition angle as the load drops off.

## • Applications

Mercury arc inverters have been used principally on d-c electric railway systems in mountainous country to provide for the regeneration of power during dynamic braking of trains. Because a single converter unit would have to have its d-c terminals automatically reversed by a heavy current switch very frequently between rectifier and inverter operation, it is a better practice to provide separate rectifier and inverter units. The inverter would normally be rated to handle the maximum current regenerated by the trains on the down grade, but the rectifier might not be capable of handling the higher currents occasionally required by very heavily loaded freight trains on the up grade. In this case, the inverter unit can be automatically switched over and paralleled with the rectifier unit.

There would be no disadvantage in occasionally switching over the inverter unit to share the peak load of the rectifier, as a train coming on to the down grade at this time would be able to regenerate its power directly to the motors of the train on the up grade. When the peak rectifier load decreased to within the rating of the rectifier unit, the inverter unit would be automatically switched back to its normal connection for inverter operation so as to be set to invert power to the a-c system whenever the rectifier load disappeared. A connection of this type provides an efficient utilization of the converting equipment.

A few other applications of mercury arc inverters have also been made, notably in industrial plants for static type Ward-Leonard drives, and in power plants for coupling two a-c systems of different frequencies together wherein a rectifier and inverter afford a completely flexible and static type link. Experiments are also in progress using mercury arc rectifiers and inverters for the transmission of power at high d-c voltages, and for rectifying three-phase power of one frequency and inverting it into single-phase power at another frequency. The future will undoubtedly see many applications for mercury arc inverter equipment.

# THE APPLICATION OF SYNCHRONOUS MOTORS TO HIGH INERTIA LOADS

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● One of the essential conditions of the successful application of any motor is its ability to start and bring the machine that it drives up to full speed. Since a synchronous motor of the usual type can carry much more load after it is in synchronism than it can bring up to speed, it is usually desirable to reduce the load as much as possible during the starting period. This is desirable from the standpoint of the design of the motor, because it will usually result in a smaller and cheaper motor; and it is also desirable from the standpoint of the power system, because considerably larger currents at much lower power factors are required to start most synchronous motors than to operate them at full load in synchronism.

Frequently the load can be materially reduced quite easily, as is the case with most reciprocating compressors, positive pressure blowers, and centrifugal pumps or blowers. There are, however, some machines, such as cement mills, that cannot be unloaded for starting, and others, such as mine fans, which have large and heavy rotating parts and can sometimes be partially unloaded. Still others, such as induced draft fans, having heavy rotating parts, cannot be unloaded very much. Each of these cases requires careful consideration, particularly those where both large starting loads and heavy rotating parts are involved.

## ● Backward field

The usual type of revolving field synchronous motor is started by applying voltage to the stator winding with the rotor circuit closed through a suitable resistance. The currents induced in the amortisseur winding with which the rotor is equipped and in the closed field circuit react upon the revolving field produced by the stator currents in nearly the same manner as in an induction motor, producing the torque necessary to bring the motor and its load to within a few percent of synchronous speed. The phenomenon is complicated somewhat by the definite pole construction with its exciting winding, which introduces a second field revolving at a speed corresponding to twice the slip.

This is called the "backward" field. It produces a component of torque which adds to the above torque below half speed and subtracts above this point. If the backward field is excessive, peculiar cusps will result in the speed-torque curve. This effect is usually unimportant in a well-designed amortisseur winding.

AT LEFT: To keep mill scale out, this 250 hp d-c motor, built to drive an edger on a bar mill, is equipped with dust filter and fan motor-mounted.

If the speed attained under these conditions is high enough, direct-current excitation can then be applied, and the machine will go to full speed and operate in synchronism; that is, it will "pull into step." The phenomena occurring during the pull-in period have been the subject of a great deal of study. The maximum slip from which it is possible to pull in depends upon the design of the motor, the inertia of the rotating parts, the characteristics of the system from which power is drawn, and the phase angle at which voltage is applied. Shoults, Crary, and Lauder* give the following expression for average slip for the most unfavorable phase angle:

$$s < k_2 \sqrt{\frac{E_d\, e}{f\, H\, (X_d + x_1)}}$$

where $s$ = Average slip just before excitation is applied

$k_2$ = 0.55 to 0.60

$E_d$ = Direct axis voltage corresponding to field excitation

$e$ = System voltage back of line reactance $x$

$x_1$ = Line reactance to point of constant voltage

$f$ = Line frequency

$H$ = Inertia constant $= \dfrac{0.231 \times WR^2 \times (rpm)^2}{kva \times 10^6}$

$X_d$ = Direct axis synchronous reactance

As shown by the above equation, the maximum permissible slip at the point where excitation is applied varies inversely as the square root of the flywheel effect. This means that if the flywheel effect is large, it becomes necessary to bring a given motor closer to synchronism than would otherwise be necessary; and the load must be correspondingly reduced.

Since "nominal pull-in torque" is defined by the American Standards Association rules as the torque developed by the motor when running as an induction motor at 95 percent speed, and "pull-in torque" is defined as the maximum constant torque under which the motor will pull its connected inertia load

* A. I. E. E. Transactions Vol. 54, 1935, p. 1385.

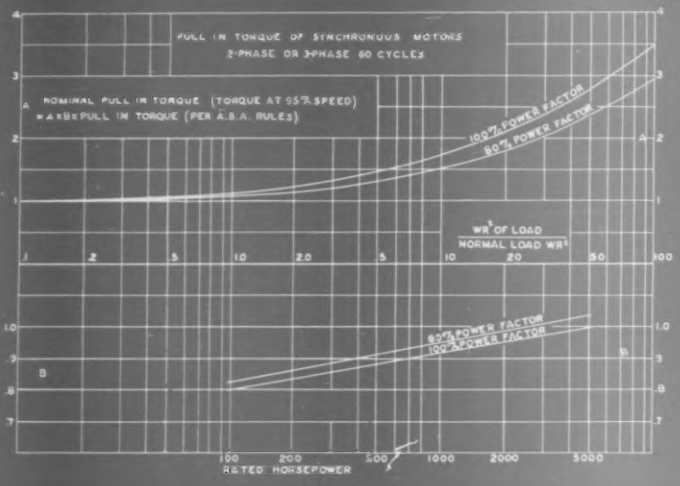

PULL IN TORQUE OF SYNCHRONOUS MOTORS
2-PHASE OR 3-PHASE 60 CYCLES
A NOMINAL PULL IN TORQUE (TORQUE AT 95% SPEED)
B PULL IN TORQUE (PER A.S.A. RULES)
100% POWER FACTOR
80% POWER FACTOR
WR² OF LOAD / NORMAL LOAD WR²
80% POWER FACTOR
100% POWER FACTOR
RATED HORSEPOWER

Fig. 1

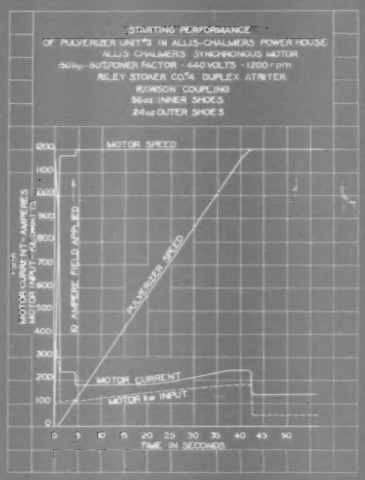



Fig. 2

into synchronism, this effect results in a larger "nominal pull-in torque" for the same "pull-in torque" under the above conditions.

## • To determine approximate "nominal" values

Unfortunately, it has become rather common to use the term "pull-in torque" when "nominal pull-in torque" is intended. For this reason especially it is desirable to be able to determine the approximate "nominal" values corresponding to the torque resulting from the load when the flywheel effect is excessive. The curves of Fig. 1 show the approximate values of the ratio of "nominal pull-in torque" to "pull-in torque" for various sizes of motors and for various values of flywheel effect for both unity and 80 percent power factor. These values are approximate only, because many assumptions were made in their derivation,* some of which may be considerably different from a particular case being considered. The Shoults, Crary, and Lauder equation above should be used for accurate work.

As is seen from the curves, the above ratio is expressed as a function of the horsepower and power factor ratings of the motor and of the ratio of the actual flywheel effect of the load to the "normal load $WR^2$," where

$$\text{Normal load } WR^2 = 3.75 \times 10^5 \frac{(\text{hp})^{1.15}}{(\text{rpm})^2}$$

which is the equation of the values adopted by N. E. M. A.* The following illustrates how large this effect may become.

It is desired to drive a certain induced draft fan with a 400 hp, unity power factor, 1200 rpm, synchronous motor. During normal operation with the exhaust gases hot, it requires 365 hp to drive it. Dampers are provided to reduce the load during starting, but on account of the necessity of starting cold the load cannot be reduced below 290 hp at full speed at the close of the starting period. The flywheel effect of the fan is 12,900 lb $ft^2$, which is 50 7 times the normal load $WR^2$ of 255 shown in the appendix for this rating. Then, referring to the curve, Fig. 1, A=2.82 and B=0.87. The nominal pull-in torque will then be approximately

$$290 \text{ hp} \times 2.82 \times 0.87 = 710 \text{ hp}$$

Therefore, a 400 hp motor having about 178 percent nominal pull-in torque must be selected, which will be very much larger than the standard motor having only 110 percent pull-in torque.

Excessive values of flywheel effect, particularly when combined with large starting and pull-in requirements, may also result in excessive heating during the starting period, which requires careful consideration in design and may necessitate special construction in certain cases.

An alternate method of handling such cases is to install a clutch of some kind between the motor and the load. This enables the motor to be started light, brought into synchronism, and fully excited before being required to develop the large torque necessary to accelerate the load. This method is best insofar as the motor and the power system are concerned, because the maximum power is not required until after the motor is in synchronism and is able to develop it at high efficiency and high power factor. This results in the smallest possible motor for the service and the minimum disturbance to the system. The difficulty is in securing a suitable clutch. Mechanical clutches of various kinds have been used with varying success. Magnetic clutches have also been used.

## • New automatic clutch

A new type of automatic mechanical clutch applicable to certain high inertia loads has been developed recently. It is a centrifugal clutch in which the shoes producing the friction are actuated by centrifugal force. As shown in Fig. 3, the distinguishing feature is that there are two sets of shoes, one set rotating with and responding to the speed of each half of the coupling. The torque developed by each set can be adjusted independently by varying the weights of the respective shoes.

When used with a synchronous motor, the outer shoes, which are connected to the driving side of the coupling, are adjusted to develop somewhat less torque at full speed than the pull-in torque of the

* See appendix.

motor. This enables the motor to accelerate rapidly and pull into step before the driven machine has attained much speed and before the inner shoes, which are connected to the driven side of the coupling, have developed appreciable torque. Then, as the speed of the load increases, the inner shoes begin to engage, and the torque increases rapidly until full speed is reached and the torque developed is sufficient to prevent any slippage. The maximum torque developed must be well under the pull-out torque of the motor; otherwise the motor would probably be pulled out of step just before the load reached full speed.

Figure 2 shows the results of starting tests made on a unit consisting of a 150 hp, 80 percent, 1200 rpm, synchronous motor driving a coal pulverizer through such a coupling. As shown, the motor comes up to speed in about 4½ seconds, but about 42 seconds is required to bring the pulverizer up to speed. The acceleration is smooth, the maximum power of about 180 kw occurring just before the pulverizer reaches full speed. The flywheel effect of the pulverizer is 6830 lb ft², which is 82.5 times the "normal load WR²" for this rating, but it is started practically empty. This is the kind of drive for which this type of coupling seems particularly well suited.

## • Appendix—ratio of nominal pull-in torque to actual pull-in torque

Using Shoults, Crary, and Lauder's equation for maximum permissible slip

$$s = k_2 \sqrt{\frac{E_d\, e}{\pi f\, H (X_d + x_1)}}$$

and taking $e = 1.00$, $k_2 = 0.55$, and neglecting $x_1$,

$$(1)\quad s = 0.55 \sqrt{\frac{E_d}{\pi f\, H\, X_d}}$$

Assuming that the slip near synchronism varies as the $\frac{3}{2}$ power of the torque, which is approximately correct for small slips,

$$(2)\quad s = 0.05 \left(\frac{T}{T_N}\right)^{\frac{3}{2}}$$

Equating (1) and (2) and solving for $\frac{T_N}{T}$:

$$(3)\quad \frac{T_N}{T} = 0.202 \sqrt[3]{\frac{\pi f\, H\, X_d}{E_d}}$$

"Normal load WR²" as adopted is equal to $3.75 \times 10^5 \frac{hp^{1.15}}{rpm^2}$

Assume that the WR² of 100 percent power factor, 60 cycle motors having 150 percent pull-out torque is

$$WR^2_{100} = \frac{9.00 \times 10^5 \times hp^{1.15}}{rpm^2}$$

and for 80 percent power factor, 60 cycle motors having 225 percent pull-out torque, it is

$$WR^2_{80} = \frac{15.00 \times 10^5 \times hp^{1.15}}{rpm^2}$$

Then for 100 percent power factor, 60 cycle motors,

$$(4)\quad H = \frac{2.31 \times (3.75K + 9.00) \times hp^{1.15}}{rpm^2} \times \frac{rpm^2 \times \eta}{0.746 \times hp \times 100} = (0.116K + 0.278)\eta \times hp^{0.15}$$

$\frac{X_d}{E_d}$ is the approximate pull-out torque for 100 percent power factor motors, which may be assumed to remain constant at 1.50 even though the motor design may be modified to give more pull-in torque. Accordingly, if this value is substituted in eq (3) for $\frac{X_d}{E_d}$ along with the value of H as determined from eq (4), and 60 for the frequency, then for 100 percent power factor, 60 cycle motors,

$$(5)\quad \frac{T_N}{T} = \sqrt[3]{\frac{0.364k + 0.872}{0.872}} \times 0.202 \sqrt[3]{34.9\, \eta\, (hp)^{0.15}} = A_{100} \times B_{100}$$

Similarly, for 80 percent power factor, 60 cycle motors,

$$(6)\quad H_{80} = (0.116 + 0.464)\, \eta \times 0.80 \times hp^{0.15}$$

and then substituting this value for H in eq (4), $\frac{1}{2.25 \times 0.80}$ for $\frac{X_d}{E_d}$, and 60 for f,

$$(7)\quad \frac{T_N}{T} = \sqrt[3]{\frac{0.364k + 1.46}{1.46}} \times 0.202 \sqrt[3]{39.0\, \eta\, hp^{0.15}} = A_{80} \times B_{80}$$

List of symbols:

- $s$ = Per unit slip
- $e$ = Per unit system voltage back of $x_1$
- $x_1$ = Per unit external reactance
- $X_d$ = Per unit direct axis synchronous reactance
- $E_d$ = Per unit excitation voltage
- rpm = Revolutions per minute at rated speed
- $T$ = Actual pull-in torque in accordance with A. S. A. rules
- $T_N$ = Nominal pull-in torque (95 percent speed)
- $K$ = Ratio of $\frac{\text{actual WR}^2 \text{ of load}}{\text{normal load WR}^2}$
- hp = Rated horsepower of motor

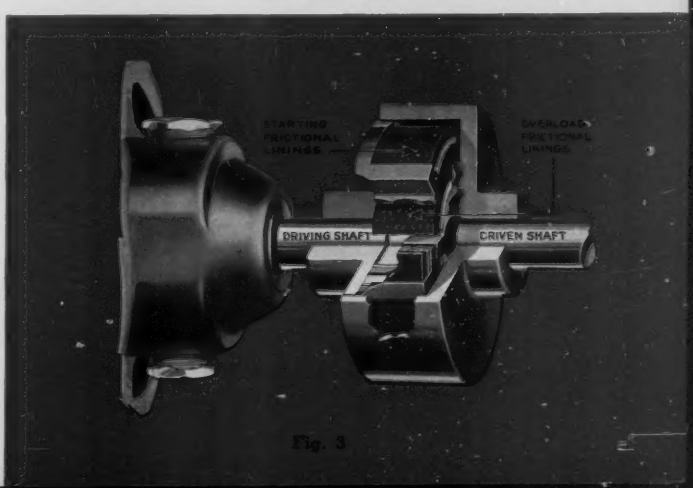


Fig. 3

$f$ = Frequency of power system in cycles per second

$$H = \frac{2.31 \times \text{total } WR^2 \times rpm^2}{kva \times 10^7}$$

$\eta$ = Efficiency

$WR^2_{100}$ = $WR^2$ of 100 percent power factor motors having 150 percent pull-out torque

$WR^2_{80}$ = $WR^2$ of 80 percent power factor motors having 225 percent pull-out torque

$$A_{100} = \sqrt[3]{\frac{0.364K + 0.872}{0.872}}$$

$$B_{100} = 0.202 \sqrt[3]{34.9\,\eta\,hp^{0.15}}$$

$$A_{80} = \sqrt[3]{\frac{0.364K + 1.46}{1.46}}$$

$$B_{80} = 0.202 \sqrt[3]{39.0\,\eta\,hp^{0.15}}$$

## Normal $WR^2$ of LOAD for 60 Cycle High-Speed Synchronous Motors

| Poles | 4 | 6 | 8 | 10 | 12 | 14 |
|---|---|---|---|---|---|---|
| RPM | 1800 | 1200 | 900 | 720 | 600 | 514 |
| HP | | | | | | |
| 20 | 3.75 | 8.1 | | | | |
| 25 | 4.63 | 10.5 | | | | |
| 30 | 5.75 | 13 | 23.1 | | | |
| 40 | 8 | 18.1 | 32.1 | 50.2 | | |
| 50 | 10.4 | 23.5 | 41.7 | 65.2 | 93.8 | |
| 60 | 12.9 | 28.9 | 51.3 | 80.2 | 115.5 | |
| 75 | 16.6 | 37.5 | 66.5 | 104 | 150 | |
| 100 | 23.1 | 52.2 | 92.6 | 145 | 209 | 284 |
| 125 | 29.9 | 67.2 | 119.5 | 186.5 | 268.5 | 366.5 |
| 150 | 36.9 | 83 | 147.5 | 230 | 331 | 452.5 |
| 200 | 51 | 115 | 205 | 320 | 460 | 627.5 |
| 250 | 66 | 149 | 264 | 412.5 | 594 | 810 |
| 300 | 82 | 184 | 327 | 512 | 736 | 1005 |
| 350 | 98 | 220 | 391 | 612 | 880 | 1200 |
| 400 | 113.5 | 255 | 455 | 711 | 1024 | 1388 |
| 450 | 129 | 290 | 516 | 807 | 1165 | 1586 |
| 500 | 147.5 | 330 | 587 | 920 | 1325 | 1800 |
| 600 | 181 | 408 | 725 | 1130 | 1625 | 2225 |
| 700 | 217 | 487 | 865 | 1350 | 1950 | 2650 |
| 800 | 253 | 568 | 1010 | 1575 | 2275 | 3100 |
| 900 | 289 | 650 | 1160 | 1813 | 2600 | 3550 |
| 1000 | 328 | 738 | 1312 | 2050 | 2950 | 4025 |
| 1250 | 422 | 950 | 1686 | 2640 | 3800 | 5175 |
| 1500 | 522 | 1172 | 2090 | 3265 | 4700 | 6400 |
| 1750 | 622 | 1400 | 2490 | 3890 | 5590 | 7625 |
| 2000 | 725 | 1625 | 2890 | 4525 | 6512 | 8875 |
| 2250 | 832 | 1875 | 3325 | 5200 | 7500 | 10250 |
| 2500 | 935 | 2100 | 3725 | 5840 | 8400 | 11450 |
| 3000 | 1160 | 2610 | 4650 | 7250 | 10470 | 14250 |
| 3500 | 1375 | 3100 | 5525 | 8625 | 12450 | 17000 |
| 4000 | 1612 | 3630 | 6440 | 10060 | 14500 | 19750 |
| 4500 | 1840 | 4130 | 7350 | 11500 | 16550 | 22500 |
| 5000 | 2090 | 4680 | 8325 | 13000 | 18750 | 25500 |

## Normal $WR^2$ of LOAD for 60 Cycle Low-Speed Synchronous Motors

| Poles | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 |
|---|---|---|---|---|---|---|---|---|
| RPM | 450 | 400 | 360 | 327 | 300 | 277 | 257 | 240 |
| HP | | | | | | | | |
| 20 | 60 | 75 | 90 | 110 | 130 | 155 | 180 | 205 |
| 25 | 75 | 95 | 115 | 140 | 170 | 200 | 230 | 265 |
| 30 | 95 | 115 | 145 | 175 | 210 | 245 | 285 | 325 |
| 40 | 130 | 165 | 210 | 245 | 290 | 340 | 395 | 455 |
| 50 | 165 | 210 | 260 | 315 | 375 | 440 | 510 | 585 |
| 60 | 205 | 260 | 320 | 390 | 460 | 540 | 630 | 720 |
| 75 | 265 | 335 | 415 | 505 | 600 | 700 | 815 | 935 |
| 100 | 370 | 470 | 580 | 700 | 830 | 975 | 1130 | 1300 |
| 125 | 475 | 605 | 745 | 905 | 1070 | 1260 | 1460 | 1680 |
| 150 | 590 | 745 | 920 | 1115 | 1330 | 1550 | 1810 | 2070 |
| 175 | 705 | 890 | 1100 | 1330 | 1580 | 1860 | 2160 | 2470 |
| 200 | 820 | 1040 | 1280 | 1550 | 1850 | 2160 | 2520 | 2880 |
| 225 | 940 | 1190 | 1470 | 1780 | 2110 | 2480 | 2880 | 3300 |
| 250 | 1060 | 1340 | 1660 | 2010 | 2380 | 2800 | 3250 | 3730 |
| 300 | 1310 | 1660 | 2050 | 2480 | 2940 | 3450 | 4010 | 4600 |
| 350 | 1560 | 1975 | 2440 | 2960 | 3520 | 4120 | 4790 | 5490 |
| 400 | 1820 | 2300 | 2850 | 3450 | 4100 | 4800 | 5580 | 6400 |
| 450 | 2080 | 2640 | 3260 | 3950 | 4690 | 5500 | 6390 | 7330 |
| 500 | 2350 | 2970 | 3670 | 4450 | 5290 | 6200 | 7200 | 8250 |
| 600 | 2900 | 3670 | 4540 | 5490 | 6530 | 7650 | 8890 | 10200 |
| 700 | 3460 | 4380 | 5410 | 6560 | 7790 | 9140 | 10600 | 12200 |
| 800 | 4040 | 5110 | 6310 | 7650 | 9090 | 10650 | 12400 | 14200 |
| 900 | 4620 | 5850 | 7240 | 8760 | 10400 | 12200 | 14200 | 16250 |
| 1000 | 5220 | 6610 | 8160 | 9890 | 11750 | 13800 | 16000 | 18300 |
| 1250 | 6750 | 8550 | 10560 | 12800 | 15200 | 17800 | 20700 | 23700 |
| 1500 | 8310 | 10500 | 13000 | 15730 | 18700 | 22000 | 25500 | 29200 |
| 1750 | 9940 | 12600 | 15500 | 18800 | 22400 | 26200 | 30500 | 35000 |
| 2000 | 11600 | 14670 | 18100 | 21950 | 26100 | 30600 | 35500 | 40700 |
| 2250 | 13300 | 16800 | 20800 | 25200 | 29900 | 35000 | 40700 | 46600 |
| 2500 | 15000 | 18900 | 23400 | 28300 | 33600 | 39600 | 45900 | 52600 |
| 3000 | 18500 | 23400 | 28900 | 35000 | 41600 | 48700 | 56600 | 65000 |
| 3500 | 22100 | 27900 | 34500 | 41800 | 49600 | 58200 | 67500 | 77500 |
| 4000 | 25700 | 32500 | 40200 | 48500 | 57800 | 67900 | 78800 | 90400 |
| 4500 | 29400 | 37200 | 46000 | 55600 | 66100 | 77600 | 90100 | 103400 |
| 5000 | 33200 | 42100 | 52000 | 63000 | 74800 | 87800 | 102000 | 117000 |

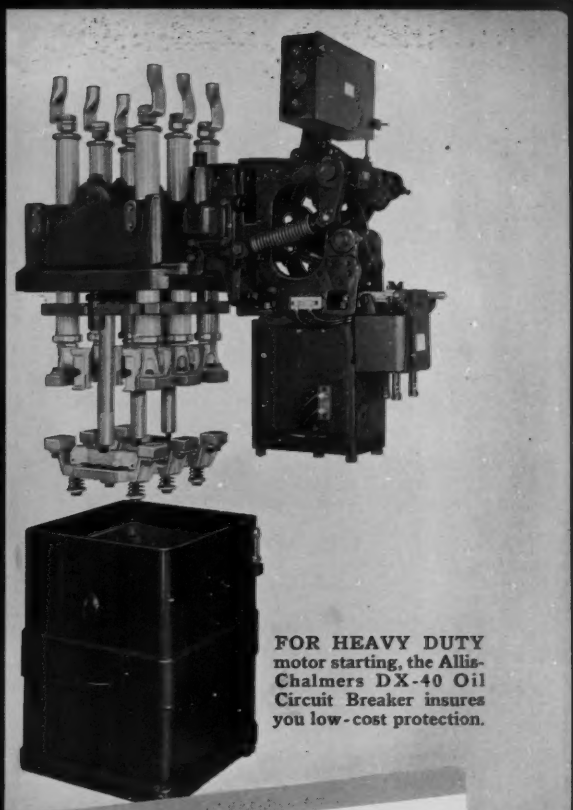
## Normal $WR^2$ of LOAD for 60 Cycle Low-Speed Synchronous Motors

| Poles | 32 | 36 | 40 | 44 | 48 | 52 | 56 | 60 |
|---|---|---|---|---|---|---|---|---|
| RPM | 225 | 200 | 180 | 164 | 150 | 138 | 128 | 120 |
| HP | | | | | | | | |
| 20 | 230 | 295 | 365 | 440 | | | | |
| 25 | 300 | 380 | 470 | 565 | | | | |
| 30 | 370 | 470 | 580 | 700 | | | | |
| 40 | 515 | 655 | 805 | 970 | | | | |
| 50 | 665 | 845 | 1040 | 1250 | | | | |
| 60 | 820 | 1040 | 1280 | 1550 | | | | |
| 75 | 1060 | 1350 | 1660 | 2000 | | | | |
| 100 | 1480 | 1870 | 2310 | 2780 | 3320 | 3930 | 4560 | 5200 |
| 125 | 1910 | 2420 | 2980 | 3600 | 4300 | 5080 | 5900 | 6710 |
| 150 | 2360 | 2980 | 3680 | 4440 | 5300 | 6260 | 7280 | 8290 |
| 175 | 2810 | 3560 | 4400 | 5300 | 6330 | 7480 | 8690 | 9890 |
| 200 | 3280 | 4150 | 5130 | 6170 | 7390 | 8730 | 10130 | 11500 |
| 225 | 3760 | 4750 | 5870 | 7070 | 8450 | 10000 | 11600 | 13200 |
| 250 | 4240 | 5360 | 6620 | 7980 | 9540 | 11300 | 13100 | 14900 |
| 300 | 5240 | 6630 | 8180 | 9850 | 11800 | 13900 | 16200 | 18400 |
| 350 | 6240 | 7900 | 9760 | 11800 | 14000 | 16600 | 19300 | 22000 |
| 400 | 7360 | 9220 | 11400 | 13800 | 16400 | 19400 | 22500 | 25600 |
| 450 | 8350 | 10550 | 13000 | 15700 | 18800 | 22200 | 25800 | 29300 |
| 500 | 9400 | 11900 | 14700 | 17700 | 21100 | 25000 | 29000 | 33000 |
| 600 | 11600 | 14700 | 18100 | 21800 | 26100 | 30800 | 35800 | 40700 |
| 700 | 13850 | 17500 | 21600 | 26100 | 31200 | 36800 | 42800 | 48700 |
| 800 | 16150 | 20400 | 25200 | 30400 | 36400 | 42900 | 49900 | 56800 |
| 900 | 18500 | 23400 | 28900 | 34800 | 41600 | 49100 | 57100 | 65000 |
| 1000 | 20800 | 26400 | 32600 | 39300 | 47000 | 55500 | 64500 | 73400 |
| 1250 | 27000 | 34200 | 42100 | 50900 | 60700 | 71700 | 83300 | 95000 |
| 1500 | 33200 | 42100 | 52000 | 62600 | 74800 | 88400 | 103000 | 117000 |
| 1750 | 39700 | 50400 | 62100 | 74800 | 89500 | 106000 | 123000 | 140000 |
| 2000 | 46300 | 58600 | 72400 | 87300 | 104000 | 123000 | 143000 | 163000 |
| 2250 | 53100 | 67200 | 83000 | 100000 | 119000 | 141000 | 164000 | 187000 |
| 2500 | 59800 | 75700 | 93500 | 113000 | 135000 | 159000 | 185000 | 210000 |
| 3000 | 73900 | 93500 | 115000 | 139000 | 166000 | 197000 | 228000 | 260000 |
| 3500 | 88200 | 112000 | 138000 | 166000 | 199000 | 235000 | 272000 | 310000 |
| 4000 | 102500 | 130000 | 161000 | 193000 | 230000 | 273000 | 317000 | 361000 |
| 4500 | 118000 | 149000 | 184000 | 221000 | 265000 | 313000 | 364000 | 414000 |
| 5000 | 133000 | 168000 | 208000 | 250000 | 299000 | 354000 | 411000 | 467000 |

## Normal $WR^2$ of LOAD for 60 Cycle Low-Speed Synchronous Motors

| Poles | 66 | 72 | 76 | 80 | 84 | 90 |
|---|---|---|---|---|---|---|
| RPM | 109 | 100 | 95 | 90 | 86 | 80 |
| HP | | | | | | |
| 100 | 6300 | 7480 | 8290 | 9250 | 10110 | 11700 |
| 125 | 8140 | 9660 | 10700 | 11900 | 13090 | 15100 |
| 150 | 10000 | 11900 | 13200 | 14700 | 16100 | 18600 |
| 175 | 12000 | 14200 | 15800 | 17600 | 19250 | 22200 |
| 200 | 14000 | 16600 | 18400 | 20500 | 22450 | 25900 |
| 225 | 16000 | 19000 | 21100 | 23500 | 25700 | 29700 |
| 250 | 18100 | 21500 | 23800 | 26500 | 29000 | 33500 |
| 300 | 22300 | 26500 | 29400 | 32700 | 35800 | 41400 |
| 350 | 26600 | 31600 | 35000 | 39000 | 42700 | 49400 |
| 400 | 31000 | 36900 | 40800 | 45500 | 49900 | 57500 |
| 450 | 35500 | 42200 | 46700 | 52100 | 57000 | 65900 |
| 500 | 40000 | 47500 | 52600 | 58600 | 64200 | 74200 |
| 600 | 49400 | 58700 | 65000 | 72500 | 79400 | 91600 |
| 700 | 59000 | 70100 | 77600 | 86500 | 94800 | 109500 |
| 800 | 68800 | 81900 | 90700 | 101000 | 110600 | 128000 |
| 900 | 79700 | 93700 | 103700 | 116000 | 126600 | 146000 |
| 1000 | 88900 | 106000 | 117000 | 130000 | 143000 | 165000 |
| 1250 | 115000 | 137000 | 151400 | 169000 | 185000 | 214000 |
| 1500 | 142000 | 168000 | 186000 | 208000 | 227500 | 263000 |
| 1750 | 169000 | 201000 | 223000 | 249000 | 272000 | 314000 |
| 2000 | 197000 | 234000 | 260000 | 290000 | 317000 | 366000 |
| 2250 | 226000 | 268000 | 298000 | 332000 | 363000 | 420000 |
| 2500 | 255000 | 303000 | 336000 | 374000 | 410000 | 473000 |
| 3000 | 315000 | 374000 | 415000 | 462000 | 505000 | 584000 |
| 3500 | 376000 | 446000 | 495000 | 552000 | 604000 | 698000 |
| 4000 | 438000 | 520000 | 576000 | 642000 | 704000 | 812000 |
| 4500 | 501000 | 595000 | 660000 | 735000 | 805000 | 930000 |
| 5000 | 566000 | 673000 | 745000 | 831000 | 910000 | 1050000 |

# 10,000 MAKES 10,000 BREAKS!



FOR HEAVY DUTY motor starting, the Allis-Chalmers DX-40 Oil Circuit Breaker insures you low-cost protection.

## Allis-Chalmers Test Engineers Verify Another Design! Read How Four Years of Oil Circuit Breaker Service Was Concentrated into Nine Short Days to Give You Motor Starting Dependability!

Oil circuit breakers for heavy motor starting duty have to be dependable . . . capable of a great number of operations under heavy load before renewal of contacts or oil is necessary.

To meet this need, Allis-Chalmers engineers designed the DX-40 Breaker . . . incorporated expulsion ports and massive butt type arcing contacts to insure interrupting efficiency . . . then turned the completed breaker over to the Allis-Chalmers testing laboratory with instructions to "give it the works" . . . operate it to the limit!

The Allis-Chalmers test engineers followed their instructions — they connected this 600 ampere breaker to a 1200 ampere load and put it to work . . . making — breaking 10,000 times. At first the CO operations were one minute apart; after 586 operations the interval was reduced to 45 seconds; and after 3344 operations, the time interval was further reduced to 10 sec.

Then the breaker "went to town!" It operated 6928 times more — a grand total of 10,858 successive operations . . . the equivalent of four years of severe service in the field . . . and without renewal of oil or contacts!

What do the results of that test mean to you! Just this — when you specify Allis-Chalmers Oil Circuit Breakers, you get better operation at lower maintenance and replacement costs . . . fewer interruptions of service!

But that's only part of the story! Let a trained engineer in the district office near you give you the complete details on the savings in time that save you money . . . with Allis-Chalmers Motor Starting Oil Circuit Breakers!

1080

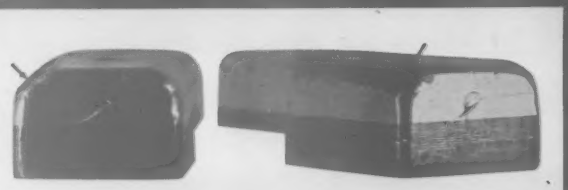
SWITCHGEAR DIVISION
ALLIS-CHALMERS
MILWAUKEE · WISCONSIN

METALCLAD SWITCHGEAR • SWITCHBOARDS • OIL CIRCUIT BREAKERS • REGULATORS • MOTOR STARTERS • CUBICLES • SWITCH HOUSES

AT THE TIME THIS ADVERTISEMENT WAS WRITTEN

# NOT A SINGLE CONTACT HAS EVER BEEN REPLACED Because of Deterioration

## on an Allis-Chalmers 5/8 % Half-Cycling Step Regulator!



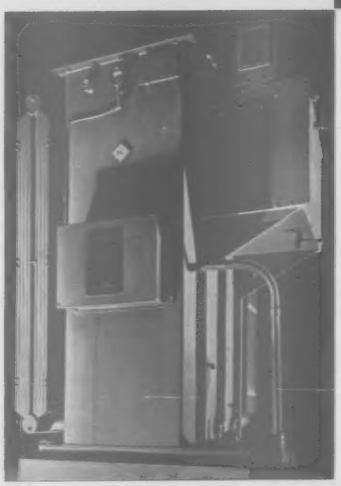
**New Records Set by Allis-Chalmers Extra Large, Non-Arcing Contacts! Get the Story of How You Can Get Smoother Regulation at Lower Cost with 5/8% Half-Cycling Step Regulators!**

**TORTURE TEST!** Unretouched photograph of an Allis-Chalmers non-arcing contact after the equivalent of 2,000,000 tap changes . . . equal to about 50 years of normal operation in the field!

• • •

**KEEPING VOLTAGE CONSTANT** for a large utility is this Allis-Chalmers 5/8% Half-Cycling Step Regulator!

• • •



Here's news for every engineer who is looking for better regulator operation at lower cost! In September, 1933, Allis-Chalmers placed 5/8% Half-Cycling Step Regulators on the market. At the time this advertisement was written, over five years later, *there has not been a single contact replaced on Allis-Chalmers regulators, due to deterioration from normal operation.*

MR. PHIL PAUL,
DALLAS OFFICE

And this service record was not unexpected! For factory tests had been run on these regulators . . . life tests . . . equivalent of 2,000,000 tap changes . . . equivalent to about 50 years of normal operation in the field! Look at that unretouched photograph of the extra large non-arcing Allis-Chalmers contact as it appeared after this test! Practically no deterioration there!

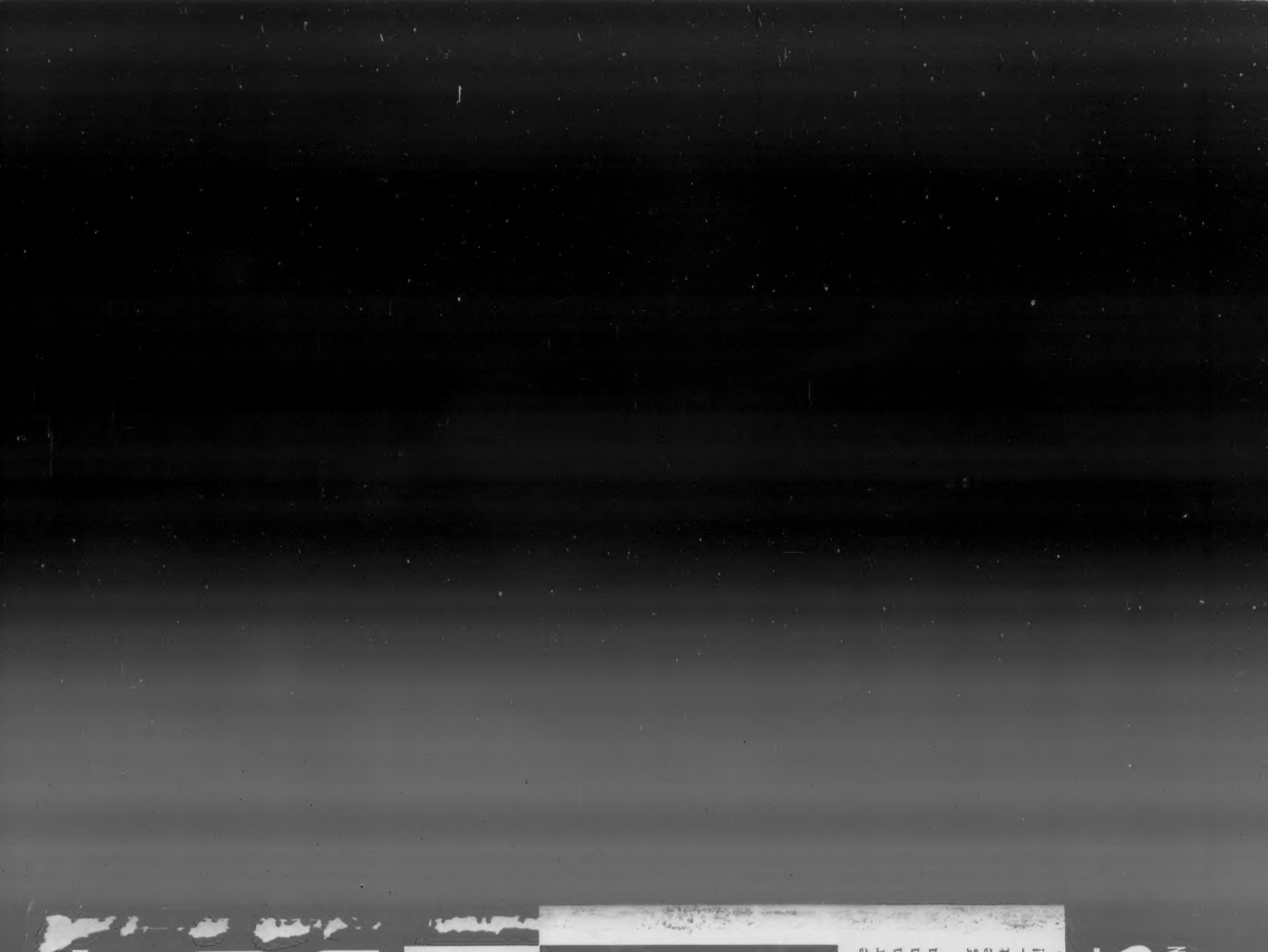
That's because Allis-Chalmers contacts are made of special non-arcing metals of proper dimensions . . . move at high speed . . . and with half-cycling operation. Add to that the smooth regulation of 5/8% Half-Cycling Steps, and you get a combination that can't be beat!

Get the facts about all the other money-saving features of Allis-Chalmers Regulators! Write for Bulletin 1170-C . . . find out how you can get smoother regulation at lower cost with Allis-Chalmers 5/8% Half-Cycling Step Regulators!

E1048

INCREASE YOUR REVENUE WITH ALLIS-CHALMERS 5/8% HALF-CYCLING STEP REGULATORS

TRANSFORMER DIVISION

ALLIS-CHALMERS

MILWAUKEE · WISCONSIN